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EVALUATION OF SHORT CRACK ARREST TEST TECHNIQUES

Final Report
by

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EXECUTIVE SUMMARY

A review of test techniques for evaluating crack arrest performance has been carried out. No universally accepted test method or method of analysis exists. Where the crack length is short, a static analysis may be adequate for many practical purposes, but a full dynamic approach is needed to explain the performance of long crack propagation/arrest behaviour.

The type of test employed should be related to the crack arrest criterion selected and the mode of crack arrest. For long crack arrest under elastic-plastic conditions the dual plate (hybrid) large size tests are most appropriate. Few practical applications would experience crack arrest under plane strain conditions as in the compact crack arrest test.

For many applications a short crack arrest criterion may be appropriate. Design of the short crack arrest specimen and testing rig is less critical than for large crack arrest tests. The short crack run suggests that a static analysis could be used. It is recommended that this type of test should be used for a program for evaluating steels intended for Arctic and offshore applications and for establishing the crack arrest capability of steels meeting the requirements of CSA S473. A survey of available facilities indicates that suitable apparatus for most types of crack arrest tests are available in Canada, and minor modifications to the wide plate rig at the Welding Institute of Canada would make it suitable for short crack arrest tests.

RESUME EXECUTIF

On a effectué une revue des techniques d'essai pour évaluer la capacité à arrêter les fissures. Il n'existe aucune méthode universelle d'essai ni d'analyse. Pour les fissures courtes, une analyse statique peut être satisfaissante pour la plupart des applications practiques, mais on a besoin d'une approche entièrement dynamique pour expliquer le comportement propagation-arrêt des fissures longues.

Le type d'essai utilisé doit être relié au critère choisi pour l'arrêt de la fissure et au mode d'arrêt de la fissure. Pour l'arrêt des fissures longues dans des conditions élasto-plastiques, les essais sur grandes tôles doubles sont les plus appropriés. Il n'y a que peu d'applications practiques où l'on retrouve l'arrêt de fissures dans les conditions de déformation plane de l'essai compact d'arrêt de fissures.

Un critère d'arrêt des fissures courtes peut être approprié pour de nombreuses applications. La conception des éprouvettes et du banc d'essai pour l'arrêt des fissures coutres est moins critique que celle pour les fissures longues. La courte propagation des fissures suggère l'utilisation d'une analyse statique. On recommande d'utiliser ce type d'essai pour un programme d'évaluation des aciers devant être utilisés dans l'Arctique et les applications offshore et pour établir la capacité à arrêter les fissures des aciers satisfaisant les exigences de la norme ACNOR S473. Un tour des facilités a montré que des équipements acceptables pour la plupart des essai d'arrêt des fissures sont disponibles au Canada, et qu'avec des modifications mineures, le banc d'essai des tôles larges à l'Institut de soudure du Canada serait adapté à l'essai d'arrêt des fissures courtes.

NOMENCLATURE

a	Crack half-length (central crack) or crack length (edge crack)
B	Specimen thickness in compact crack arrest test
B_N	Net specimen thickness in compact crack arrest test
c	Crack length (= $2a$)
CAT	Crack arrest temperature
D	Total energy dissipated in the system
d	Distance elastic wave travels
δ	Crack mouth opening displacement
E	Young's modulus
G	Strain energy release rate
K	Stress intensity factor
K_{ca}	Arrest toughness from static analysis
K_D	Dynamic toughness
K_{IC}	Plane strain initiation toughness under static loading rates
K_{Id}	Plane strain initiation toughness under dynamic loading rates
K_{Ia}	Plane strain crack arrest toughness
K_{Im}	Minimum value of dynamic toughness
L	Length of plate in wide plate test (normal to direction of crack)
NDTT	Nil-ductility transition temperature
R	Fracture resistance
S	Effective surface energy
σ	Applied stress
T	Temperature (°K for exponential expressions)
T	Kinetic energy
τ	Time
t	Plate thickness
U	Elastic strain energy
ν	Poisson's ratio
W	Width of specimen
W	External work done by the system

Evaluation of Short Crack Arrest Test Techniques

Introduction

This project arose from an interest in determining what types of crack arrest tests would be most appropriate for evaluating steel for Arctic and offshore applications in Canada. The need to demonstrate some level of crack arrest capabilities in steel for critical applications is inherent in the toughness requirements of CSA S473 - (Code for the Design, Construction, and Installation of Fixed Offshore Structures, Part III - Steel Structures) and has been considered necessary for other structures such as ships. Fracture tests, particularly large scale crack arrest tests, can be very expensive so careful selection of test technique is important in planning cost effective programs. The present project was undertaken, therefore, to review crack arrest test methods and to recommend techniques suitable for evaluating steels for Canadian applications. For ease of reference, a description of the major crack arrest tests is included in a separate Appendix.

Background

The majority of toughness specifications for critical structures are related, although not necessarily explicitly, to a need to ensure the arrest of cracks initiating around welds. For many specifications written in terms of Charpy Vee notch (CVN) requirements, this relationship is through the Fracture Analysis Diagram of Pellini [1] shown in Fig. 1. The Fracture Analysis Diagram sets the minimum temperature relative to the nil ductility transition temperature (NDTT) at which a crack is arrested for a given average applied stress.

In developing toughness requirements for CSA S473 [2] it was desired to maintain the same general philosophy of crack arrest capability, but because the correlation between NDTT and CVN could not be trusted for modern steels the requirements have been specified directly in terms of NDTT. The NDTT as determined by the drop weight test indexes the toughness/temperature curve, and this approach assumes this curve to be independent of the material. Such a temperature shift method means that toughness test performance (i.e. NDTT) is specified at a temperature different from the minimum design temperature, and therefore the test does not directly measure crack arrest capability at the design temperature.

A review [3] of a large amount of crack arrest data shows that, in general, the NDTT based requirements do ensure a reasonable level of crack arrest capability, but there are still uncertainties regarding effects of thickness, crack size, and influence of steel type. To gain confidence in the requirements specified it will be necessary to directly measure the crack arrest performance of relevant steels. It will also be necessary to specify more clearly the crack arrest criteria appropriate for various types of structures.

Literature Survey

A list of relevant papers was assembled using the Engineering Index and Weldasearch databases through CAN/OLE and Dialog. Additional information was also obtained by direct contact with a number of sources listed at the end of the reference section. The database of crack arrest literature is given in Table 1, but several are secondary references since not all documents could be obtained because many were not available in Canada through regular channels. In this section some of the key work on crack arrest is discussed with particular emphasis on the types of laboratory tests used. Some of the theoretical aspects of dynamic crack propagation and arrest are highly complex and are beyond the scope of the present study, but basic theoretical ideas will be discussed.

Crack Arrest Temperature Concept

Interest in crack arrest behaviour of steel increased as a result of ship fractures during World War II and failures in other structures such as pipelines and storage tanks. Initial work on ship fractures was aimed at characterizing materials that would give low probability of failure in service. Based on data from service casualties, this led to the 15 ft. lb. CVN energy criterion in the USA [4] and the standard grades of ship steels in the U. K. [5]. At the same time there was an effort to develop laboratory tests in which the crack propagation and arrest behaviour could be studied.

Robertson [6] at the Naval Construction Research Establishment (U.K.) developed one of the first crack arrest tests (shown in Fig. A-1, in the Appendix). Original tests were carried out with a temperature gradient across the specimen. The plate is stressed to a given level then a fracture initiated on the cold side by impact loading. The fracture progresses across the specimen until it reaches warmer material that is sufficiently tough to arrest the crack. This method of testing gave rise to the concept of crack arrest temperature (CAT). Early work suggested that the crack arrest temperature was independent of stress above a minimum stress needed to drive the crack and was also independent of the crack length. This behaviour is illustrated by some typical results reported by Wells [7] and shown in Fig. 2.

A difficulty with temperature gradient arrest tests is determining the location of the arrest. In Robertson tests this is identified with the position of the shear lips on the plate surface. Examination of a typical crack front profile at arrest (Fig. 3) shows that

this position is displaced from the crack tip at the centre of the plate. This difference is small when arrest occurs at low applied stresses but becomes significant when stresses are high and arrest is associated with large shear lips. To avoid ambiguity in defining the arrest position, tests can be carried out under isothermal conditions on a 'go/ no go' basis with several tests being performed to bracket the crack arrest temperature. The results of isothermal tests show a stronger dependence on temperature as illustrated schematically in Fig. 4.

The crack arrest temperature (CAT) as determined by Robertson (or similar) tests is an important part of the Fracture Analysis Diagram method of Pellini [1]. The right hand boundary (CAT curve) of the diagram is regarded as the limit beyond which unstable fracture cannot occur. This line is independent of crack size and is therefore believed to be the arrest curve appropriate for very long cracks.

The CAT curve depends on the plate thickness and moves to higher temperatures with greater thicknesses [8]. Because of the cost of establishing the CAT curve using large scale tests, Pellini proposed a method for estimating the position of the curve from fracture mechanics [9]. This method was based on the observation that crack arrest occurred under elastic-plastic conditions as evidenced by the large shear lips present. Crack arrest, therefore, is associated with loss of plane strain constraint and does not occur under linear elastic conditions. In Pellini's method, which has recently been reviewed elsewhere [3], the position of the CAT curve is found from the plane strain (initiation) fracture toughness determined under dynamic (high loading rate) conditions by considering the effect of thickness on the plane strain capacity. The dynamic initiation toughness is considered appropriate since it is argued that the crack will not propagate unless it can (continually) reinitiate. Fracture mechanics is used only to define the stress state/temperature transition and not to imply any relationship between the stress and the size of arrested crack.

One of the criticisms of the Robertson test was the method of crack initiation which involved impact on one side of a hole (Fig. A-1). It was thought the shock waves from such an impact could influence the test results. An alternate test which used a separate loading system to initiate the crack was proposed by Yoshiki and Kanazawa[10] and is known as the double tension test. This has become a standard test in Japan and provides the largest database of crack arrest properties. The design of the initiation plate in the double tension test is such that the load on it has virtually no effect on the stress in the main test plate, and there is no impact that could cause shock waves.

The test (described in the Appendix) can be used with a temperature gradient in

which case Japanese practice has been to take the crack front at the mid-thickness as the arrest point. This could be at least 30°C displaced from the shear lip position on the plate surface used in the Robertson test [11]. The stress/temperature curve is therefore displaced to the right of that produced from Robertson temperature gradient tests and to the right of isothermal tests with either the Robertson or double tension configuration (see Fig. 4). The isothermal tests are essentially 'go/no go' types with the cracks either running completely across the plate or arresting shortly after entering the propagation part of the specimen.

Crack Arrest Toughness Concept

The difference in behaviour between temperature gradient and isothermal tests was rationalized by Koshiga [11] using static linear elastic fracture mechanics arguments and gives rise to the crack arrest toughness concept, K_{ca}. Using the Irwin formulation, the work done by the elastic stresses when the crack moves forward by an amount Δa is

$$\frac{(1 - \upsilon^2)}{E} K^2 \Delta a$$

(Terms are defined at the beginning of the report).
If the effective surface energy of the crack is S (for both surfaces), then instability occurs when

$$\frac{(1 - \upsilon^2)}{E} K^2 > S$$

In the crack arrest toughness concept it is assumed that the above expression becomes an equality at the point of arrest, and the value of K becomes a material property representing the crack arrest toughness, K_{ca}. For an edge cracked plate of finite width, the value of K is given by:

$$K = \sigma \sqrt{2W \tan\left(\frac{\pi a}{2W}\right)}$$

where W is the width of the plate. Thus K_{ca} can be determined by measurement of the crack length at arrest in the double tension test. Koshiga found that, when expressed in this form, data from both temperature gradient and isothermal tests fell on the same line (Fig. 5). Of course, isothermal tests that completely fracture do not yield a value of K_{ca}

and only the 'no go' results where short cracks arrest on running into the test plate provide a K_{ca} value.

Following the suggestion of Akita and Ikeda [12] that the effective surface energy should depend on temperature in the following form:

$$S = S_0 \exp(-k/T)$$

it was found that K_{ca} data also followed a similar equation:

$$K_{ca} = K_0 \exp(-T_0/T)$$

where K_0, T_0 are material constants.

Typical results from Koshiga [11] are shown in Fig. 5. It was noticed that for a given class of steels, (e.g., ferrite-pearlite steels) the slopes of the lines (i.e., T_0) were approximately constant, and thus the crack arrest properties of the steel could be characterized by the single parameter, K_0.

The presentation of data in this form meant that K_{ca} could be determined from gradient tests which require a lot less specimens than the isothermal tests. Most Japanese crack arrest data has been presented in this form, and double tension gradient tests have routinely been carried out by steelmakers. Minimum temperatures for suitable crack arrest performance are often quoted by steelmakers on the basis of a K_{ca} = 186 MPa$\sqrt{m}$ (600 kg.f.mm$^{-3/2}$) criterion.

The value of K_{ca} (or K_0) depends on the plate thickness, and some typical early Japanese data is given in Fig. 6 where K_0 is expressed relative to the value of K_0 for 30 mm thick plate. Using 30 mm as a reference point it is common practice to 'correct' the K_{ca} values at different thicknesses to eliminate the thickness effect. The equations used in WES 3003 "Evaluation Criterion of Rolled Steels for Low Temperature Application" (which are not quite the same as those in Fig. 6) are:

$$\frac{K_0}{K_0\,(30)} = 1 - 0.05\,(t - 30) \qquad t \le 35 \text{ mm}$$

$$= \frac{54}{65} - \left(\frac{3}{1\,300}\right) t \qquad 35 < t \le 100$$

It is of interest to compare the shift in the crack arrest temperature implied by the WES 3003 formula with that inherent in the Pellini approach [9]. The comparison is shown in Fig. 7. There is considerable difference in the proposed thickness effects. The WES 3003 curve is based on ferrite-pearlite steels and other steels may have a much stronger dependence of crack arrest temperature on thickness.

The significant implication of the K_{ca} approach is that the crack arrest temperature at a given stress depends on the crack length. This is contrary to the original conclusions of the Robertson tests and led to experiments with wider test plates. Results showed that for wider plates the apparent K_{ca} toughness was much higher than that determined from standard temperature gradient double tension tests (500 mm wide). An example of these results has been presented by Kanazawa et al [13] and is shown in Fig. 8. Crack speed measurements (Fig. 9) show that higher velocities are attained for most of the crack propagation in the wider specimens than in the standard test. On this basis it was believed that dynamical effects came into play in the larger tests that served to invalidate the static fracture mechanics analysis.

To get round this discrepancy it was suggested that an 'effective' crack length could be used when the crack length exceeded about 200 mm. The idea was that a long running crack did not create the same elastic energy release rate as predicted by static fracture mechanics but behaved like a shorter crack. The value of the effective crack length was determined experimentally by calibrating the results of long arrested crack tests to the standard double tension tests. Results are shown in Fig. 10 where considerable scatter is evident.

A more useful representation is the effective K_{ca} values as shown in Fig. 11. K_{aff} is determined from the standard test and K_{app} is computed from the wide plate tests at the same temperature using the static fracture mechanics equation. The use of K_{aff} instead of effective crack length allows the concept to be applied to a crack propagating through an arbitrary stress field due to mechanical crack arresters, residual stresses etc., for which effective crack length is not relevant.

It is of interest to note that the curve in Fig. 11 appears to reach a maximum value, although it is emphasized that this curve is empirical and has no theoretical basis. This suggests that when the crack is large further extension of the crack does not increase the rate of strain energy release at the crack tip, and also implies that the strain distribution remains constant relative to the crack tip. Dynamic analysis that takes into account the speed of elastic waves through the material tends to support this contention [13].

Introducing dynamic effects greatly complicates the analysis and there has, therefore, been considerable interest in pursuing the static approach. This assumes that all dynamic effects including inertia, reflected waves, and kinetic energy can be neglected, and the total energy for fracture is provided by strain energy release that can be calculated from static fracture mechanics. The work of Crosley and Ripling [14] is most relevant in this context and has led to the development of a standard test for determining the crack arrest fracture toughness [15].

The starting point is to assume (as Wells stated [16]) that arrests are simple reversals on the time scale of possible plane-strain initiations. Just as K_{Ic} (plane strain initiation toughness) is determined from the load and crack length just prior to initiating a running crack, K_{Ia} (plane strain arrest toughness) can be determined from the same parameters just after an arrest event. Just before initiation and just after arrest the specimen is in static equilibrium and dynamic effects are considered as dynamic disturbances superimposed on the static response during the propagation phase. Inherent in this view is the assumption that the specimen and the crack come to rest at the same time and that the kinetic energy of the specimen is not recovered for crack propagation. Thus the energy available for crack extension at the point of arrest is the strain energy as represented by the stress intensity factor just after arrest. Extensive testing has been undertaken to confirm whether K_{Ia} determined in this way is a useful material property (independent of geometry) and has resulted in the ASTM standard for the compact crack arrest test. This test is described more fully in the Appendix.

The concept of arrest toughness determined through static analysis was also proposed by Wells [16] in rationalizing the length of arrested cracks in the wide plate tests. Since the wide plate tests included a longitudinal weld, the crack moved through a residual stress field which was superimposed on the applied stress field. Wells calculated the combined stress intensity factor as a function of crack tip distance from the weld centreline (Fig. 12). Unless the applied stress was very high, the value of K reached a peak just outside the weld then dropped before increasing again further away from the weld.

Experiments using the wide plate test showed that cracks often arrested in the region where the value of K decreased, and the estimated value of K at these locations was reasonably independent of stress and crack length suggesting it could be regarded as a material property representing the crack arrest toughness.

Dynamic Effects

The main ideas in the dynamic approach are best described by energy considerations, and the papers of Hahn et al. [17] provide useful illustrations. In a dynamic situation the total energy, D, dissipated in the system for an increment da of crack growth, from conservation laws, is

$$\frac{dD}{da} = \frac{dW}{da} - \frac{dU}{da} - \frac{dT}{da}$$

where W is the work done by the external loads
U is elastic strain energy
T is kinetic energy

A dynamic analysis assumes the kinetic energy is available for crack propagation and also requires that the strain energy release rate ($G = -dU / da$) is determined from a dynamic analysis that includes the effect of elastic wave velocity. The difference between the dynamic and static approach is illustrated in Hahn et al [17] for the double cantilever beam specimen (Fig. 13). In this specimen the crack runs into a field of decreasing K and arrests.

Fig. 13(a) illustrates the (static) arrest toughness approach in which arrest occurs when the static strain energy release rate equals the material fracture resistance. Kinetic energy stored in the specimen during crack propagation is lost and does not contribute to crack extension. In Fig. 13(b) the kinetic energy is available for crack extension and is fully recovered. The crack arrests at the point when all available kinetic energy is fully recovered. In Fig. 13(c) the dynamic strain energy release rate (which may be a function of crack velocity) is considered which leads to a further crack arrest criterion. In these illustrations the effect of work done by external loads has been neglected.

In order to evaluate the various terms in a dynamic analysis, a number of models have been proposed [18, 19, 20] a full description of which is beyond the scope of this present review. The dynamic analysis leads to a value for the dynamic crack extension resistance or toughness which is usually expressed as

$$K_D \left\langle = \left(\frac{ER}{1-\upsilon^2}\right)^{1/2} \quad \text{where } R \text{ is the resistance} \right\rangle$$

This represents an apparent dynamic stress intensity factor and includes more than the

strain energy release contribution to crack extension.

As an example, results from a dynamic analysis the results of Kanazawa et al. [19] for wide plate tension tests are presented in Fig. 14, which shows the relative contribution of strain energy and kinetic energy to crack extension. In Fig. 15 the dynamic fracture toughness and crack velocity are shown as a function of crack extension. Also shown is the statically determined toughness K_s which is substantially higher than K_D. The crack velocity is fairly constant across the specimen, and the increase in K_D is likely due to the temperature gradient.

It is now well established that the dynamic fracture toughness K_D is a function of crack velocity having the general form typified by the results of Kanazawa shown in Fig. 16. This behaviour seems to be independent of specimen type. A minimum value of K_D is observed for crack velocities below a few hundred m/sec. The minimum value K_{Im} can be considered a material property representing the arrest potential of the material since any drop of (dynamic) K below K_{Im} will result in arrest.

Crack arrest tests, such as the compact crack arrest test that measures K_{Ia}, can therefore be considered as attempts to obtain approximate estimates of K_{Im} by using simplified analysis. The same can be said of initiation tests that use high strain rate and measure K_{Id}.

Considerations in Crack Arrest Test Design

The simulation of fracture processes in the laboratory has been a difficult challenge particularly where long cracks are concerned. The three main areas of concern have been:

- changes in the stress intensity factor distribution as the crack/width ratio becomes large
- stored energy in the system
- reflection of elastic waves.

Wells considered the first two points (although not in the same terminology) when designing the first wide plate rigs. Overall elongation in the wide plate rig was quite small because of the system of loading but sufficiently long specimens were needed to provide representative crack propagation. Wells [21] considered the strain energy release rate of a plate at a given stress when a crack runs across it. His results are shown in Fig. 17 and indicate that the strain energy release rate depends on the ratio of width to

length and crack length to width. In order to simulate an infinite plate, the specimen length would have to be about three times the width (for a central crack), but Wells chose a square plate as a compromise. With the introduction of the K formulation for stress intensity factor this problem disappears since K can be calculated for a finite plate, and such corrections for width are normally applied to double tension test results.

The second area of concern is the effect of stored energy in the system and the influence of specimen length on the distribution of K. If the fracture process requires a greater amount of energy than can be supplied by the local relaxation of elastic strain, then continued extension of the crack depends on the supply of energy from the system remote from the crack. If a test were being conducted under 'fixed grip' conditions (i.e., a stiff testing machine such as the wide plate rig) arrest may occur in the test although arrest may not occur in practice. In such a test a load drop would be recorded following arrest. As shown in another section, wide plate rigs may only store enough energy to completely fracture plates under quite brittle conditions and may not be suitable for full, long crack arrest testing of modern steels. For short crack arrest, however, the energy requirements are far less demanding. In practice, additional loads may be applied to the crack to force continued propagation, such as flap opening as in a burst pipeline, and bulging in tanks. These are not usually simulated in laboratory crack arrest tests.

For a plate of finite length L, and width W, with a central crack of half length a, and initial applied stress σ, the expression [16] for K is

$$K = \frac{\sigma(W \tan\frac{\pi a}{W})^{\frac{1}{2}}}{(1 + \frac{4W}{\pi L} ln.sec\frac{\pi a}{W})}$$

The term in the denominator takes account of the drop in stress as the crack proceeds due to the finite length of the specimen. In this expression, the length L, is the effective length assumed to exist between fixed grips. In practice L is greater than the specimen length because of the testing machine compliance. For large scale tests it is common practice to include a correction factor for load drop effects when determining K_{ca}.

The third area of concern is the effect of elastic stress wave reflections. As the crack propagates, the material behind the crack tip is unloaded, and an unloading stress wave moves out from this region. This wave can be reflected from surfaces and boundaries in the specimen and return to the crack tip where it is superimposed on the main load. If the reflected wave is an 'unloading' wave the net stress at the crack tip is reduced and the crack may prematurely arrest. Reflections from the free surfaces at the

edges of the specimen involve a change of sign and thus unloading stress waves become loading stress waves on reflection. Waves striking the ends of the specimen where it is attached to larger end plates are reflected without change of sign and remain unloading waves.

To ensure the complete propagation-arrest event takes place without the influence of reflected waves, the specimen must be made sufficiently large. Crack velocities range 500 - 1 000 m/s in double tension tests and up to 2 000 m/s for wide plate tension tests. The crack rapidly arrests when the speed drops below 300 ~ 500 m/s. Taking 500 m/s as a conservative lower limit for average crack velocity, the duration τ of the propagation event is

$$\tau = \frac{a}{500} \qquad \text{where } a \text{ is the crack run length in metres}$$

If the velocity of elastic waves is of the order 5 000 m/s the minimum path distance d that can be travelled without causing a disturbance at the crack tip is

$$d = \tau \times 5\,000 = \frac{a \times 5\,000}{500} = 10 \times a \qquad \text{(in metres)}$$

Since the wave must travel to the boundary and back, the distance from the crack to the nearest fixed boundary at the end of the specimen is conservatively estimated at five times the crack run length. For higher crack velocities the distance can be shorter. For example, Kawaguchi et al. [22] measured a constant crack speed of 1 210 m/s in a large size hybrid (dual plate) tension test with a crack run of 1 500 mm. The minimum length of test plate calculated on the above basis is

$$2 \times \frac{d}{2} = \frac{1\,500}{1\,210} \times 5\,000 \equiv 6\ m$$

The test plate actually used was 4.8 m so it is possible that some effects of reflected unloading waves could be felt.

Short Crack Arrest

The concept of short crack arrest has been developed by Tanaka et al. [23, 24] and the test methods avoid many of the problems discussed above. In his method a running crack is injected into a plate or a weld from a separate starter section as in a double tension test. Details of the test are provided in the Appendix. It is conducted as a 'go/no

go' test, but Tanaka has estimated K values as a function of the crack length which has allowed some quantitative evaluation of the results. Fig. 18 shows an example of K estimated for two stress levels and including residual stress from the weld. The arrest toughness of the steel is assumed to rise from the plane strain value in the brittle zone to the plane stress value which it is assumed is reached when the crack penetrates twice the plate thickness. These two values were determined with compact crack arrest tests with and without side grooves respectively [24].

Large scale short crack arrest tests showed propagation at a stress of 260 MPa and arrest at the lower stress of 160 MPa. Comparison of the K curves with the estimated K_a curve in Fig. 18 indicates that the short crack arrest has been achieved by both a decrease in the applied K when the crack moves out of the residual tension field of the weld and an increase in arrest toughness due to plane stress conditions.

The use of the compact crack arrest test to measure a plane stress arrest toughness is questioned since arrest under the decreasing K field of the compact crack arrest test could give a different mode of arrest. Tanaka [24], in fact, has presented a comparison between various test results and the compact crack arrest test (Fig. 19). Reasonable agreement is seen for low toughness values but the apparent toughness seems to be underestimated at high values.

Arrest Mode

The mode of crack arrest raises the question of how crack arrest data from various tests could be applied in practice. Crack arrest can occur for two basic reasons: increase in fracture resistance of the material or decrease in the driving force. In the former case where a crack is propagating under relatively high stress the arrest on running into tougher material is associated with a change of stress state. The constraint is lost at the edges of the crack and shear lips begin to form. The crack moves ahead in the plate centre forming a tunnel, and the shear lips increase until the crack arrests. Because of the strain rate sensitivity of yield stress in ferritic steels, the plastic zone can be quite small when the crack is running fast. On slowing a bit, the yield stress drops, and the plastic zone increases in size. This further reduces the speed and the crack rapidly drops. Thus once the process of arrest has started it is completed quite quickly.

This association of crack arrest with the loss of plane strain constraint has been used by Pellini [9] as a simple means of estimating the location of the crack arrest temperature curve from high strain rate initiation toughness data or from the fracture appearance of dynamic tear tests.

In contrast, fully plane strain arrests may be obtained if arrest occurs under a decreasing K field (driving force). This is the situation in the compact crack arrest test, and the plane strain arrest toughness obtained is considered a material property independent of thickness. With a plane strain arrest no large shear lips form and there is no tunnelling—the crack front being straight and normal to the plate surface.

In practice, plane strain arrests are not likely for large cracks, and it is probable that only small pop-ins of a few millimetres might experience a plane strain arrest. Cracks running out of a brittle zone of a weld into tougher material, even when accompanied by a decrease in driving force, experience plane stress arrests as the short crack arrest test shows. This raises the question of how plane strain arrest data from compact crack arrest tests could be used in practice for normal welded steel structures. Like the plane strain initiation toughness K_{Ic}, the plane strain arrrest toughness is too low to be of practical value in structural steels. It can, of course, be used to define a lower bound of toughness, particularly for thick sections as has been done with the ASME reference toughness curve.

For the purpose of defining material property requirements for structures based on a crack arrest capability, it is recommended that the tests simulate the arrest mode and load conditions to be experienced in practice. This implies that large size tests are necessary whether of the long or short crack arrest type. Small scale tests such as compact crack arrest, drop weight, or high strain rate initiation tests (instrumented Charpy) could be used to index the crack arrest temperature curve. Alternatively, non plane strain dynamic initiation tests, such as dynamic J tests, could be used to seek correlations with the crack arrest properties.

Characteristic Joints

In discussing the desired crack arrest performance, the type of structure and joint details must be considered. To assist in defining appropriate crack arrest criteria, a few specific cases have been considered and will be discussed here. The discusson presupposes that the structure can tolerate an arrested crack and that a non-arrested crack would result in collapse. The question of tolerance to arrested cracks is beyond the scope of this report, but it may mean that crack arrest has to be evaluated at several stages in the crack progression process. For example, it may need to be shown that both short and large cracks could be arrested in the structure.

Shell Structure

The first example is a shell structure made from welded plates (Fig. 20) and subject to tension in one direction. This has been well studied since it represents both a ship hull and a storage tank. Vertical welds are staggered so there is no continuous seam normal to the direction of stress. A crack arrest criterion applicable to this situation would be that a crack propagating completely across one plate would arrest on entering the next. Propagation across one plate might occur in the weld, perhaps along the heat affected zone (HAZ). The stress is considered constant across the plate except for the horizontal seam weld where an additional tension residual stress might aid crack extension. Arrest of the crack, therefore, results completely from an increase in toughness.

The length of the crack to be arrested would be typically up to about 3 m. With such a length additional forces from bulging could some into play, but it can be argued that if arrest occurs quickly (within a few milliseconds) they do not have time to develop and can be neglected. The usual practice to simulate this situation is to use a dual plate or hybrid large size tension test with long crack runs of a metre or more. To simulate a 3 m crack in practice the test requires a 1.5 m crack run because it is an edge crack. As pointed out previously, this also requires long specimens of 5 ~ 6 m to avoid effects of reflected waves.

Values of crack arrest toughness K_{ca} from a static analysis do not agree with those from smaller tests but can be related through the empirical effective K_{ca} concept. This allows the required K_{ca} to be determined for other plate widths in a practical situation. This criterion may be regarded as long crack arrest, and at these crack lengths the crack size has little effect.

Tubular Joint

The second situation considered is a tubular joint (Fig. 21) comprising a Tee section. It is assumed that a crack could initiate in the HAZ of the weld. This might arise from a fatigue crack at the toe of the brace to chord weld. The stress concentration factor is high at this spot, and welding residual stresses may be high. If a crack propagates a large distance before arresting, the reserve strength of the tubular connection is greatly reduced. Furthermore, there is no change of material beyond the weld to provide an arrest opportunity due to increased toughness.

Arrest is therefore required in the area immediately adjacent to the weld where stresses are very high but crack lengths would be short. If arrest does not occur at this

point, the crack will continue to run until it arrests through a decrease in stress. In addition to the parent steel, it might be required that the HAZ possess adequate arrest toughness to stop the propagation of a brittle crack around the weld.

Both conditions lend themselves to testing with the short crack arrest test, either using plates or using tubular sections. In the latter case the connection can be simulated closely, and a short brittle crack injected into the HAZ using a separate crack starter section. A groove on the inside would force the fracture to continue for a desired distance before being allowed to arrest. As an alternative, the stress concentration and local stress distribution could be simulated in a flat plate using combined tension and bending. Thus the short crack arrest criterion might be an appropriate basis for the crack arrest requirements for the can sections of tubular structures.

Fractures from a Secondary Member

The third case considered involves crack initiation in a secondary member. One example of fracture initiation in secondary members associated with local damage is very relevant to the design of short crack arrest tests. The particular case was observed (1 June, 1989) on the CCG icebreaker Louis St. Laurent which had suffered local damage due to impact. Bending of the stiffeners had been sufficient to initiate a fracture at the toe of a weld attaching a bracket (Fig. 22). The fracture completely traversed the stiffener and ran across the stiffener to shell (hull) welds. The fracture is shown in Fig. 23. The crack in the flange is completely brittle and appears to originate at the stress concentration afforded by the bracket. Judging by the lack of paint flaking off and the small opening displacement of the crack in the flange, it appears that the strain in the flange was not excessively high when it fractured.

The crack, as seen in Fig. 23, completely traverses the web stopping in the shell weld. It is understood that the shell material at this location is Grade E and is 50 mm thick. This part of the ship is well above the water line and would be subject to the low environmental temperatures of the Arctic. It is not known precisely how the damage occurred or what the stresses in the shell would be at that location, but the fact that the crack ran completely up to the shell suggests a significant tensile stress existed.

The example is important since it shows a clear need for a crack arrest capability in the shell material. Initiation was not prevented, and although the stiffener was subjected to high bending, such damage conditions ought to be presumed to be part of normal icebreaker service. The significant feature is that the crack is brittle in the flange

and therefore a running crack which only arrested on running into presumably tougher material. The total run length was about 300 mm.

It is not known whether the weld joining the stiffener to the shell was a reinforced groove weld or a fillet weld. The latter is most likely and would offer an advantage in arresting the crack. If the weld was a complete penetration weld then material toughness changes would provide the main means of arresting the crack.

The example is significant in illustrating how fracture initiation can occur in secondary members and how the integrity of the structure relies on crack arrest in the shell. It is also significant in that the arrest in the shell is of the 'short crack arrest' type. That is, after injecting a running crack into the shell, the crack must arrest very quickly. If it does not, it is likely to run completely across a shell plate before having a second opportunity to arrest.

The similarity between this example and the Tanaka short crack arrest test is clear, and except for the use of tension instead of bending the Tanaka test can be said to simulate the practical condition quite closely. This also raises the possibility of performing such a test in bending with a view to simulating the practical case even more closely.

Facilities for Crack Arrest Testing

The objective of this part of the work was to determine what facilities existed in Canadian laboratories for conducting crack arrest tests and what capabilities existed for specialized, large scale testing. No attempt was made to identify all the facilities available or laboratories that had experiences in crack arrest testing but enough laboratories were surveyed to demonstrate that most types of crack arrest tests could be carried out in a Canadian laboratory.

The tests and the corresponding facilities fell into two groups: the small scale tests such as the compact crack arrest test (CCA) and large scale, specialized tests such as the wide plate test or full scale simulations. The survey indicated that capabilities exist in Canada for performing a wide variety of crack arrest tests but that experience is rather limited. There is some experience in small scale testing but no large scale tests of the wide plate type have been conducted. Details of some specific capabilities are given below. It should be pointed out that several laboratories have experience of dynamic initiation tests such as drop weight or explosion bulge tests, but the following survey concentrates on tests specifically designed to evaluate crack arrest.

Small Scale Tests

Many laboratories have the facilities for doing small scale tests such as the compact crack arrest test since only conventional testing equipment of typically 250 kN is required. The wedge method of loading provides enough load amplification that thicknesses up to several inches can be tested.

Ontario Hydro Research (Toronto) has substantial experience in carrying out compact crack arrest tests [25,26] and participated in the Round Robin Program that was conducted prior to formalizing the ASTM Standard Test Method. Ontario Hydro Research has experience with both aluminum and ferritic materials. The set-up is illustrated in Fig. 24 which fits on a 250 kN servohydraulic testing machine. A hold-down plate is included to facilitate wedge extraction during incremental load cycling. Thin sheets of trifluoroethylene resin (teflon) are used to lubricate the wedge, split pin, base plate, and specimen hole. The crack mouth opening displacement is measured with a displacement gauge at 0.25 W from the load line, where W is the specimen width. The method of starting the crack depends on the type of material being tested. In one program on an aluminum alloy [26] a starter notch was spark machined to produce an in-

cluded angle of 30° and a root radius of approximately 0.4 mm. In tests on ferritic materials [27] a brittle weld of the type used in drop weight tests was deposited across the specimen thickness. The brittle bead was then notched by spark machining to an angle of 30°, depth 2 mm and root radius about 0.2 mm. For high strength steels it was found that a simple machined notch without the brittle starter bead was adequate. Starter notches are designed to sustain sufficiently high crack opening displacement to permit an appropriate crack jump length prior to arrest. For tests at low temperature the specimen is cooled by cooling coils embedded in the support base. Specimens are insulated and temperatures on the top and bottom surfaces are measured with thermocouples.

The Materials Technology Centre of Fleet Technology Limited (Kanata) has facilities for carrying out compact crack arrest tests and is currently investigating the possibilities of setting up test facilities for doing short crack arrest (SCA) tests.

The maximum size of specimen that can be accommodated for small scale tests is 300 × 300 mm, and the servohydraulic test system has a capacity of 623 kN and a stroke of 147 mm. Temperature control is obtained using either heating/cooling pads or a cooling chamber. Outputs from the test machine, loads and clip gauge readings are monitored using a high speed scanner and a microcomputer and chart recorder. The staff at Fleet Technology Limited have extensive accumulated experience in fracture testing and T. Jutla participated in the Round Robin Program while at The Welding Institute (UK).

Several other laboratories have facilities for compact crack arrest tests but lack direct experience in performing these tests.

Large Scale Tests

Many large scale testing rigs have been custom built for specific applications, such as the pipe bending facilities at WIC and NOVA's burst test facility. Both these could be useful in crack arrest tests for investigating particular geometries. For large scale testing of plates in tension, a number of machines are available in the Universities, and the Wide Plate facility at WIC is appropriate for certain types of crack arrest tests. The Centre for Frontier Engineering Research (C-FER) will also have unique testing facilities available in 1990, but no details are known at present. As an example of large tension testing machines the Baldwin universal testing machine in the Structures Laboratories, Department of Civil Engineering, University of Toronto is given. The machine is illustrated in Fig. 25 and has the following specification:

Location:	Mark Huggins Laboratory	
Type:	Hydraulic	
Capacity:	Compression:	5338 kN
	Tension:	5338 kN
Stroke:		914 mm
Action:		Monotonic
Operating Pressure:		11,700 kPa
Maximum specimen size between grips:		
Compression:		6.7 mm
Tension:		6.7 m – stroke = 5.8 m
Clearance between columns:		3.05 m
Lateral clearance:		Open
Data output and sensor type:		
Load:	DC volts	Sensor: Load cell
Stroke:	DC volts	Sensor: LVDT
Test bed capacity:		1330 kN vertical down.

The capacity of this machine in tension would be adequate to conduct standard double tension tests (500 mm wide) at a stress of 300 MPa in plate thicknesses up to 35 mm.

The test rig most easily adapted for undertaking short crack arrest tests is the wide plate facility at the Welding Institute of Canada (WIC). The apparatus is based on the Wells design using four hydraulic capsules for loading, and the compact design results in a relatively stiff system. The wide plate facility was originally designed for fracture initiation studies where the criterion for minimum plate size was based on retention of the residual stress field.

The dimensions of the rig are given in Figs. 26 and 27, and a photograph of a fractured specimen in the rig is shown in Fig. 28. In conventional fracture initiation studies the load transferred to the specimen must be capable of taking it beyond yield since the specimen may exceed yield before failure. To achieve this without excessively large attachment devices, the specimen plate is welded directly to the end pieces using electroslag welding in the vertical position. The following summarizes the specifications for the rig:

- loading in uniaxial tension
- 4 × 1,000 metric ton loading capsules
- capacity : 39,200 kN maximum tension

- specimen: width: 1220 mm max.
  length: 1220 mm
- hydraulic capsules are in balanced arrangement and actuated independently
- plate is freely supported
- test duration is typically 15 minutes
- low temperatures attained by cooling boxes on both sides of test specimen
- clearance system to absorb outward velocity of 5 m/s.

The capacity is such that in testing plates up to a maximum stress of 400 MPa, a maximum thickness of 75 mm can be accommodated. For a maximum stress of 300 MPa, the thickness could be increased to 100 mm but at the expense of some clearance either side of the specimen.

A number of relatively simple modifications would need to be made in order to perform short crack arrest tests. The first is the need for the starter loading system which would have to fit into a space about 125 mm wide. Since only small jacks would be required to load the crack starter this space limitation should not be a problem. It would, however, require special design and evaluation before being used on an actual test.

The second point is that the short crack arrest test as used in Japan is only 420 ~ 600 mm wide, less than half the width of the wide plate specimen. This might allow redesign of the attachment system to facilitate specimen connection and removal. The conventional method of attaching plates using full strength electroslag welds is time consuming, and set-up of specimens is a major part of the total cost. With narrower specimens that do not need to be stressed to yield, pins or bolts could be used for attachment. A reusable end plate could be made, and a series of test plates drilled with matching holes prepared before commencing the test program. This would facilitate set-up and substantially reduce the cost of the tests.

The important consideration in using the wide plate test for crack arrest evaluations is the amount of stored energy. The design of the rig results in a relatively stiff system in which the end loading components can be considered as essentially fixed. Little energy would be supplied by the system beyond those end pieces, thus the only energy available for fracture is the elastic energy stored in the test plate itself. In Table 2 the total elastic stored energy is estimated for a specimen loaded to a tensile stress of 350 MPa. The equivalent energy per unit cross-section of area is determined for various specimen lengths under fixed grip conditions. If it is assumed that all the elastic energy

is available for fracture, the energy per unit area represents the maximum specific fracture energy. This is expressed in units of MPa.m and $J.m^{-2}$ and for comparison also in terms of equivalent energy for the area of a Charpy specimen. The assumption that all elastic energy is available for fracture is not likely to be valid, for a total release of energy is accompanied by decreasing stress. Fracture energies are thus likely to be somewhat less than the figures estimated in Table 2.

For the maximum specimen length that can be accommodated in the WIC wide plate rig, the maximum specific fracture energy is about 5×10^5 $J.m^{-2}$ or about 50 J for the area of a Charpy specimen. It can thus be concluded that the rig is only capable of fracturing a specimen if fracture occurs under relatively brittle conditions. With modern, clean steels even small amounts of ductile fracture (shear lips) can raise the specific fracture energy above 5×10^5 $J.m^{-2}$.

In the context of crack arrest tests this limited elastic energy means that for long propagating cracks much of the energy in the systems is used up before the opportunity for arrest occurs. If arrest occurs it may well be due to the lack of driving force. This may not represent the situation in practice, and any crack arrest toughness value (K_{ca}) determined from initial stress conditions is likely to be invalid.

If, however, arrest occurs after only short runs, the loss of energy from the system is quite small, and the crack arrest could be considered a valid event. It is concluded that the wide plate rig (at WIC) would be suitable for performing short crack arrest tests where the test is treated as a 'go/no go' test. If arrest occurs within a short distance (a few times the plate thickness), it is treated as valid. If arrest does not occur within this distance, then arrest is assumed not to have occurred whether or not arrest occurs at some further point across the specimen. Results could be validated by conducting a few extra tests with specimens of greater width.

Conclusions and Recommendations

The present review has shown that several approaches to crack arrest are being pursued, and there is no universally accepted test method or method of analysis. The concept of crack arrest toughness K_{ca}, calculated on the basis of static fracture mechanics does not work when the crack length becomes large, although for short cracks it may be sufficiently accurate for many practical purposes. Empirical relations are necessary for projecting the results from standard size tests (500 mm wide) to larger plate sizes. Significant advances have been made for full dynamic analysis, but since the dynamic toughness depends on the history of crack propagation, dynamic analysis does not lend itself to a general basis for material toughness requirements.

For most cases of practical interest, crack arrest in structural steels is associated with a stress state transition, and arrests do not usually occur under plane strain conditions. The plane strain crack arrest toughness determined with the compact crack arrest test may therefore be of only limited value in predicting behaviour of real structures. The test may be useful in establishing the transition temperature at which plane strain conditions are lost and where apparent toughness increases rapidly. In this sense it could play a similar role to the drop weight test, but having the advantage of being carried out on full thickness specimens.

For many applications a short crack arrest criterion may be appropriate, and the short crack arrest test has many advantages over other long crack run tests. Design of the specimen and testing rig is less critical because the crack run length is so short that little energy is consumed and reflected waves are unlikely to have an effect. The short crack run suggests that a static analysis could be used. Furthermore base metal and various parts of the weld may be tested. It is recommended that this type of test is the most suitable for a program for evaluating steels intended for Arctic and offshore applications and for establishing the crack arrest capability of steels meeting the requirements of CSA S473. The most suitable apparatus is the wide plate test rig at the Welding Institute of Canada, and only minor modifications would be needed before it could be used for short crack arrest tests.

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Table 2. Total elastic strain energy of plate specimens loaded to 350 MPa.

Length (m)	Specific fracture energy (MPa.m)	($J.m^{-2}$)	Equivalent CVN energy (J)
0.3	0.088	88×10^3	8.8
0.5	0.146	146×10^3	14.6
1	0.292	292×10^3	29.2
1.8 (WIC rig)	0.526	526×10^3	52.6
2	0.584	584×10^3	58.4
5	1.46	$1\,460 \times 10^3$	146

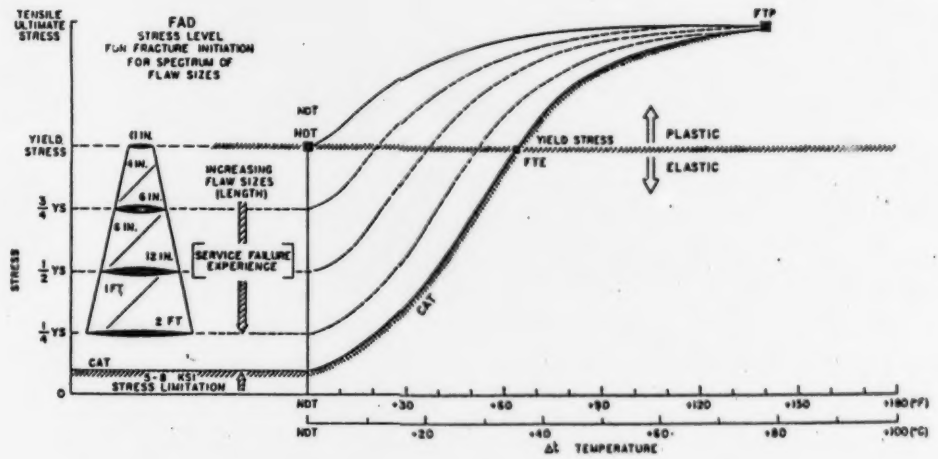

Figure 1. The original Fracture Analysis Diagram proposed by Pellini (1)

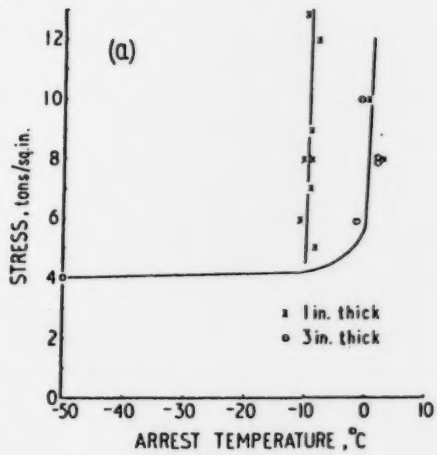

Figure 2. Typical Robertson test results, after Wells (7).

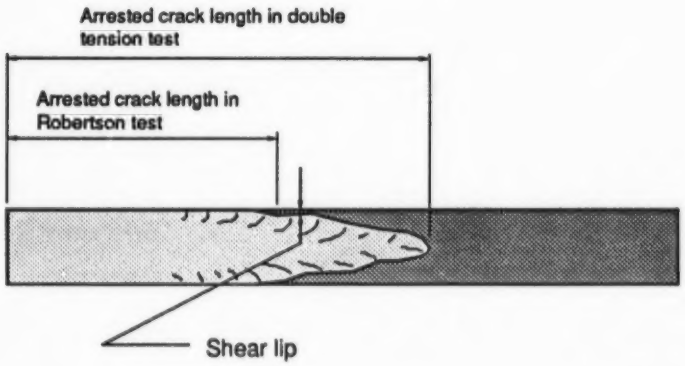

Figure 3. Typical crack front profile after arrest.

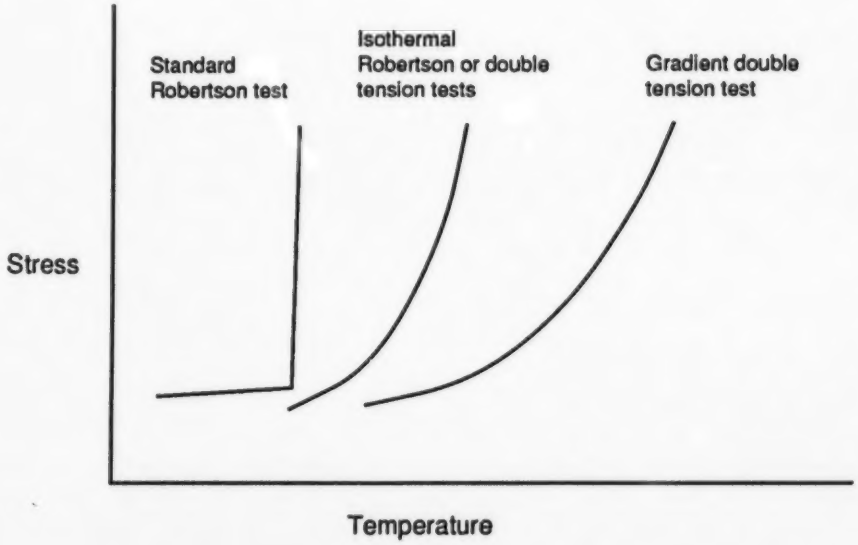

Figure 4. Crack arrest curves determined from isothermal and temperature gradient tests.

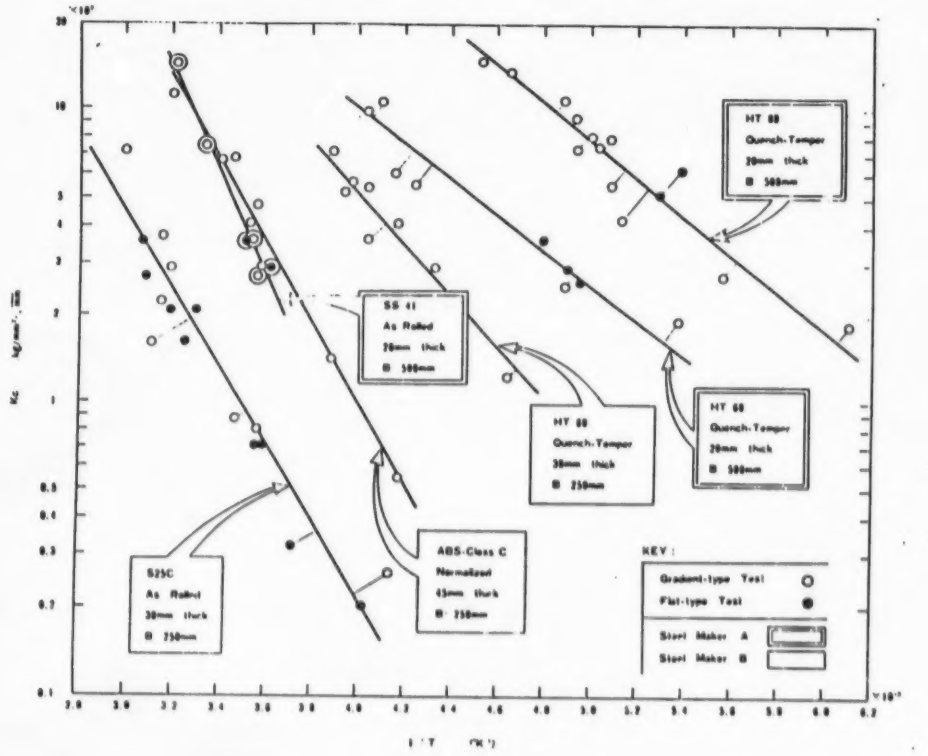

Figure 5. Results from both isothermal and temperature gradient double tension tests expressed as K_{ca} (ref. 11).

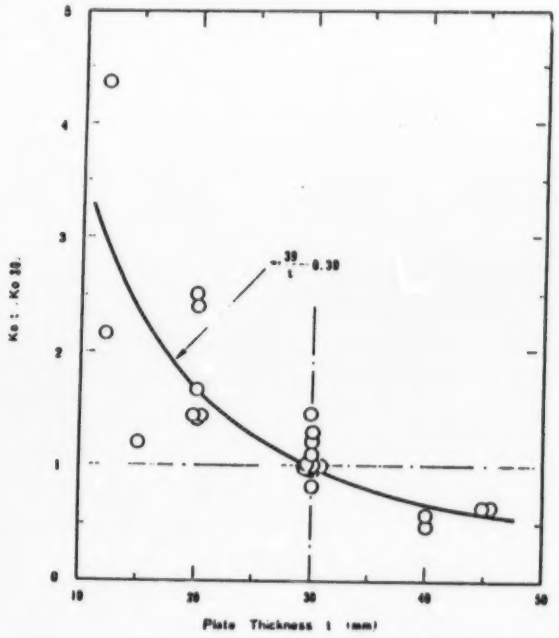

Figure 6. Effect of thickness on crack arrest toughness from double tension tests.

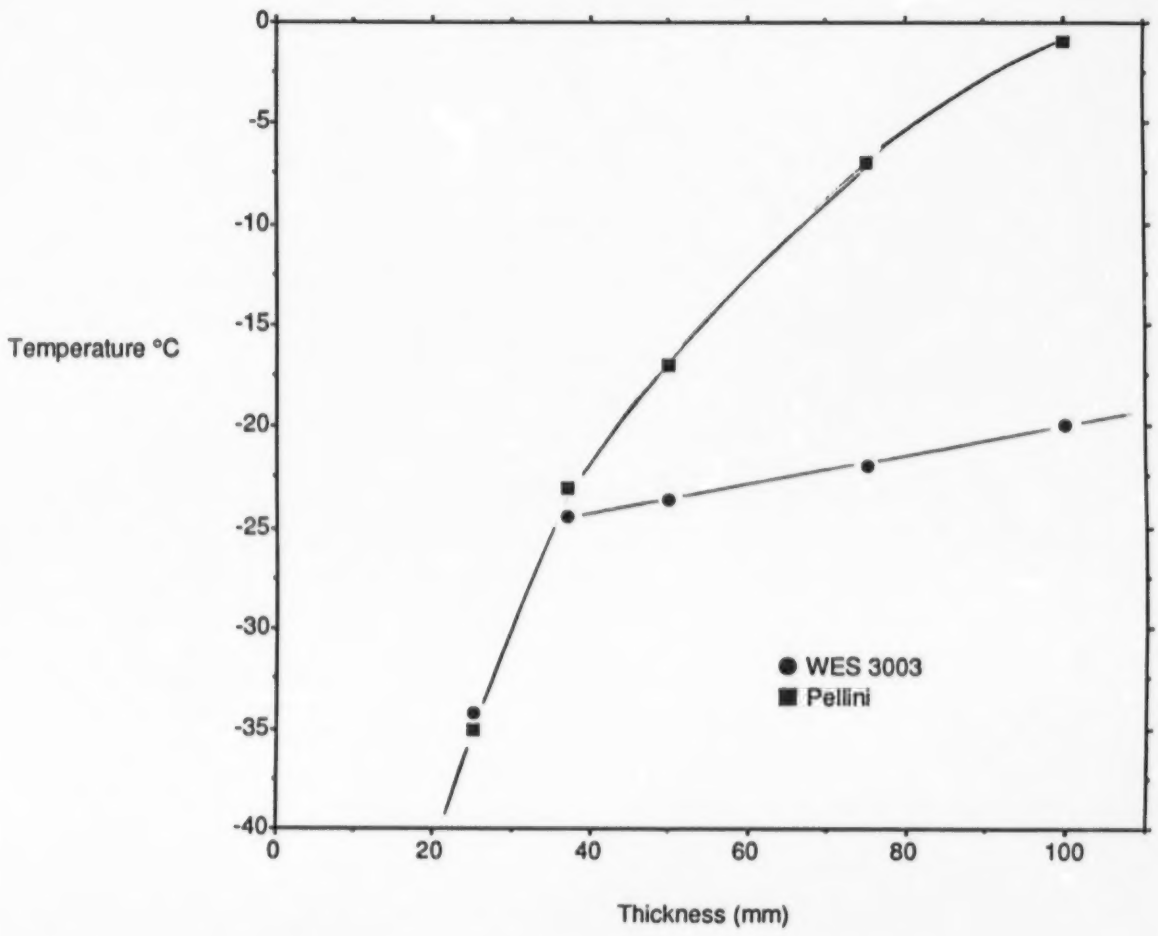

Figure 7. Effect of thickness on crack arrest temperature according to Pellini and to WES 3003. Data has been adjusted to coincide at –30°C for 30 mm thickness.

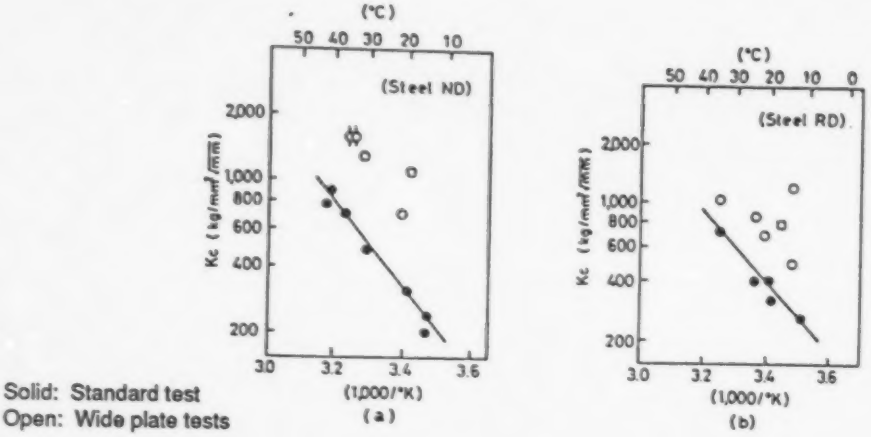

Figure 8. K_{ca} values measured from tests of different widths showing high apparent values for very wide plates (ref. 13).

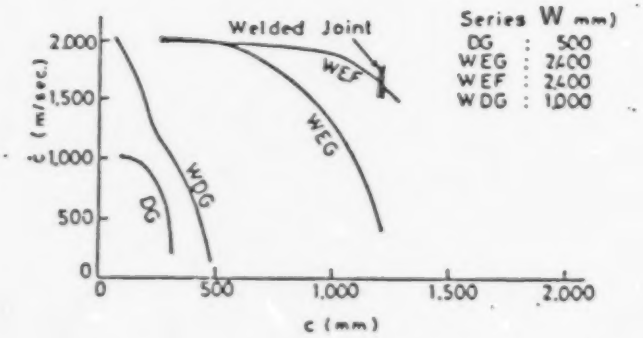

Figure 9. Crack speed measurements in tests of various sizes (ref. 13).

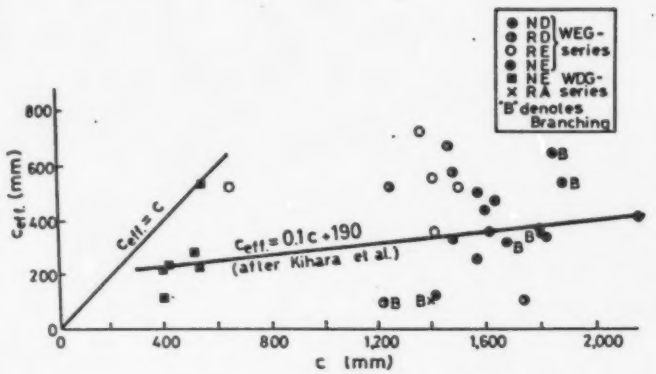

Figure 10. Results from arrest tests of various sizes expressed in the form of effective crack length.

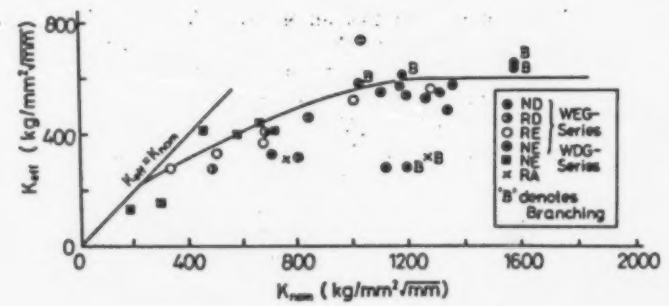

Figure 11. Results from arrest tests of various sizes expressed as effective K_{ca}.

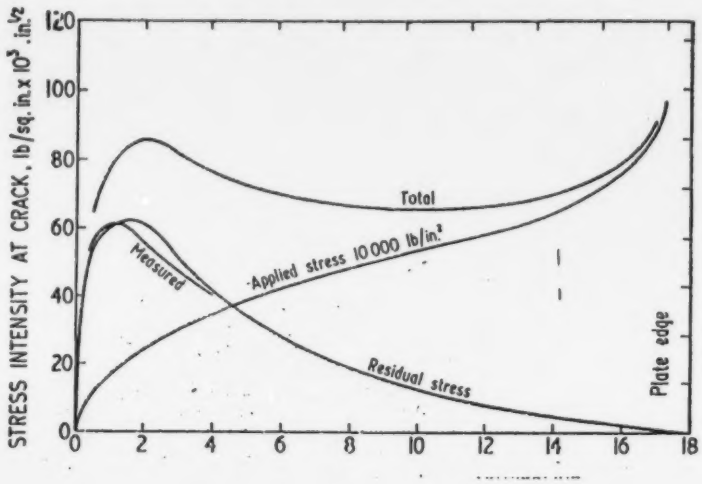

Figure 12. Calculated stress intensity factors as a function of crack tip distance from the plate centreline for wide plate tests stressed to 69 MPa (10 000 lb/in²).

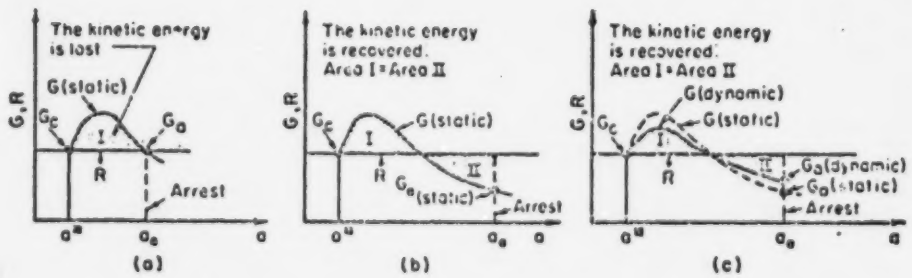

Figure 13. Illustration of energy contributions to fracture in the double cantilever beam specimen.

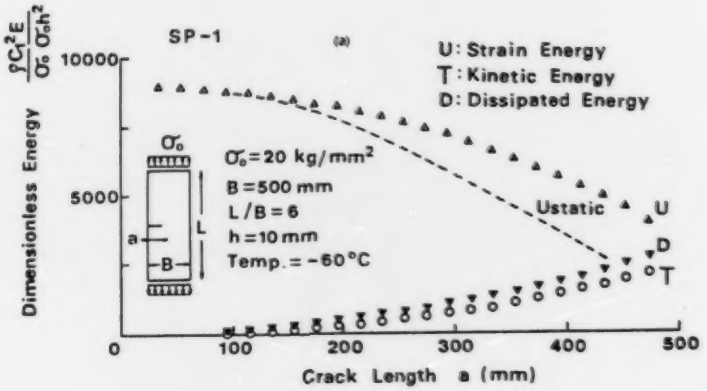

Figure 14. Energy contributions to crack extension from dynamic analysis (ref. 19).

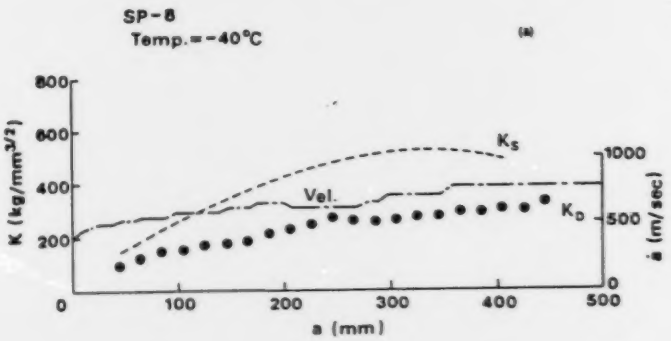

Figure 15. Dynamic fracture toughness and crack velocity as functions of crack extension from dynamic analysis (ref. 19).

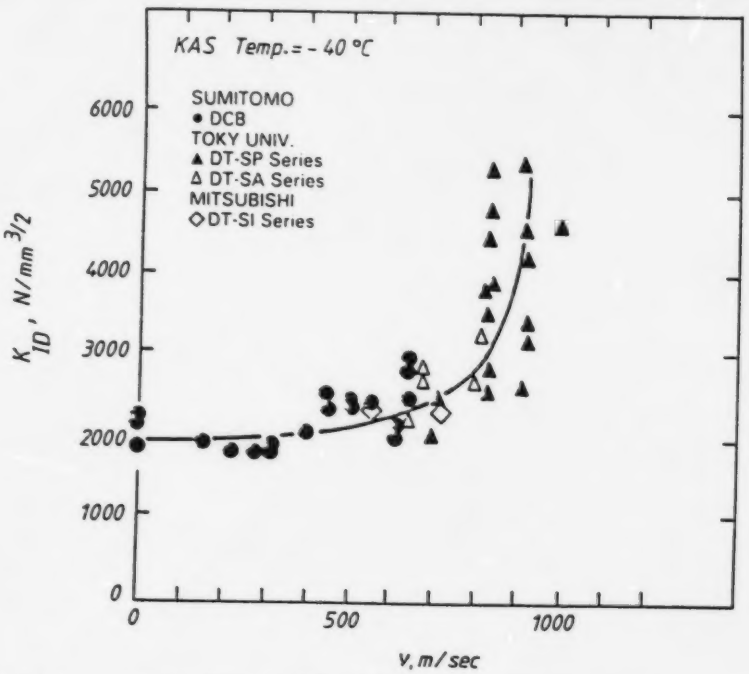

Figure 16. Dependence of K_D on crack velocity (ref. 19).

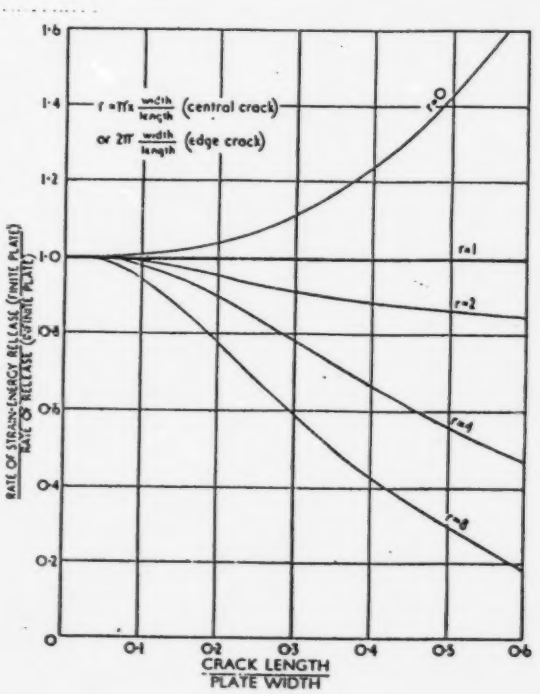

Figure 17. Strain energy release rate in Wells wide plate test for various plate sizes (ref. 21).

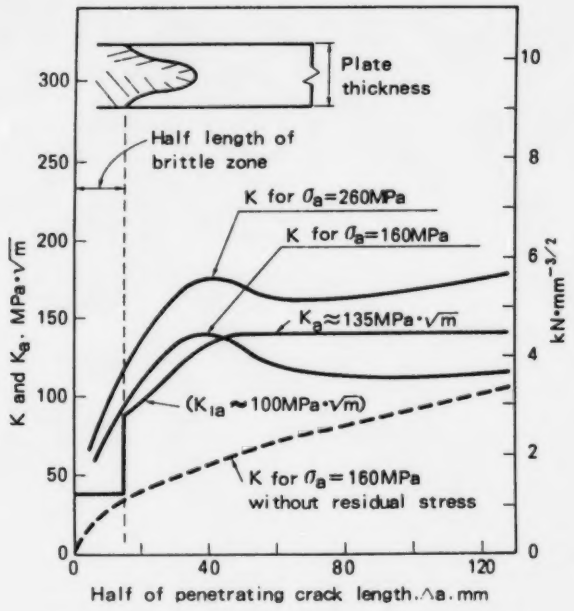
Plate thickness
Half length of brittle zone
K for σ_a=260MPa
K for σ_a=160MPa
$K_a \approx 135 MPa \cdot \sqrt{m}$
$(K_{Ia} \sim 100 MPa \cdot \sqrt{m})$
K for σ_a=160MPa without residual stress
K and K_a, MPa·√m
kN·mm$^{-3/2}$
Half of penetrating crack length, Δa, mm

Figure 18. Schematic illustration of comparison between the material's arrest toughness (denoted K_{Ia} and K_a above and K_{ca} in the text), and the net driving force K, for the short crack arrest test with a longitudinal weld (ref. 24).

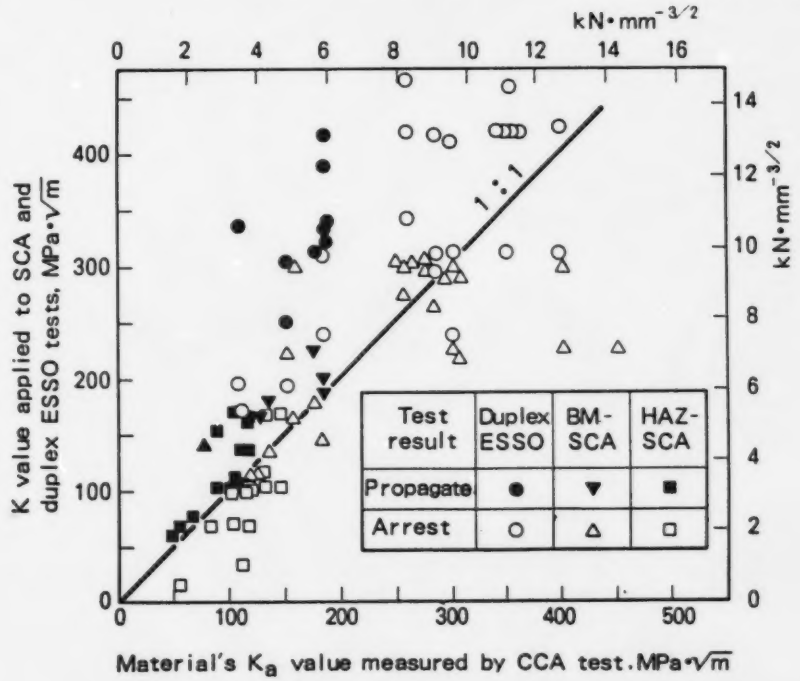
kN·mm$^{-3/2}$
K value applied to SCA and duplex ESSO tests, MPa·√m
kN·mm$^{-3/2}$
1 : 1
Test result | Duplex ESSO | BM-SCA | HAZ-SCA
Propagate
Arrest
Material's K_a value measured by CCA test, MPa·√m

Figure 19. Comparison of arrest toughness results from various wide plate tests with those from the compact crack arrest test (ref. 24).

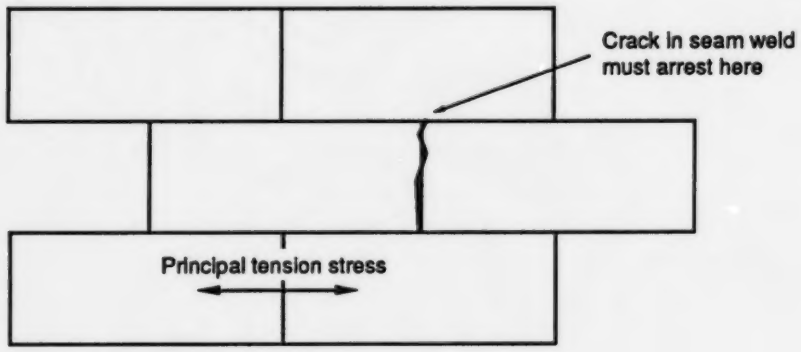

Figure 20. Shell structure of welded plates.

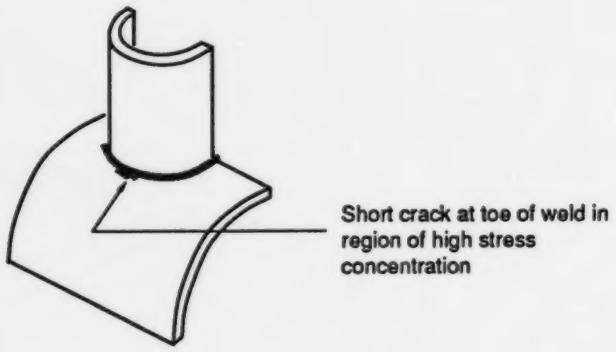

Figure 21. Tubular joint with crack initiation at the weld toe under high local stresses.

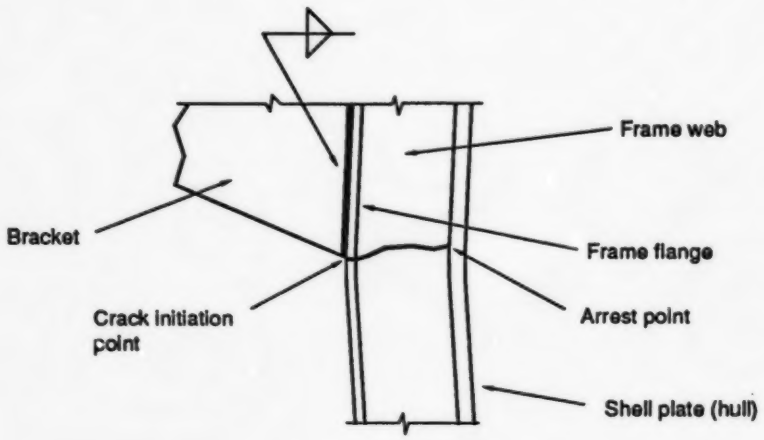

Figure 22. Illustration of initiation and propagation of a fracture in a ship frame member due to bending from local damage.

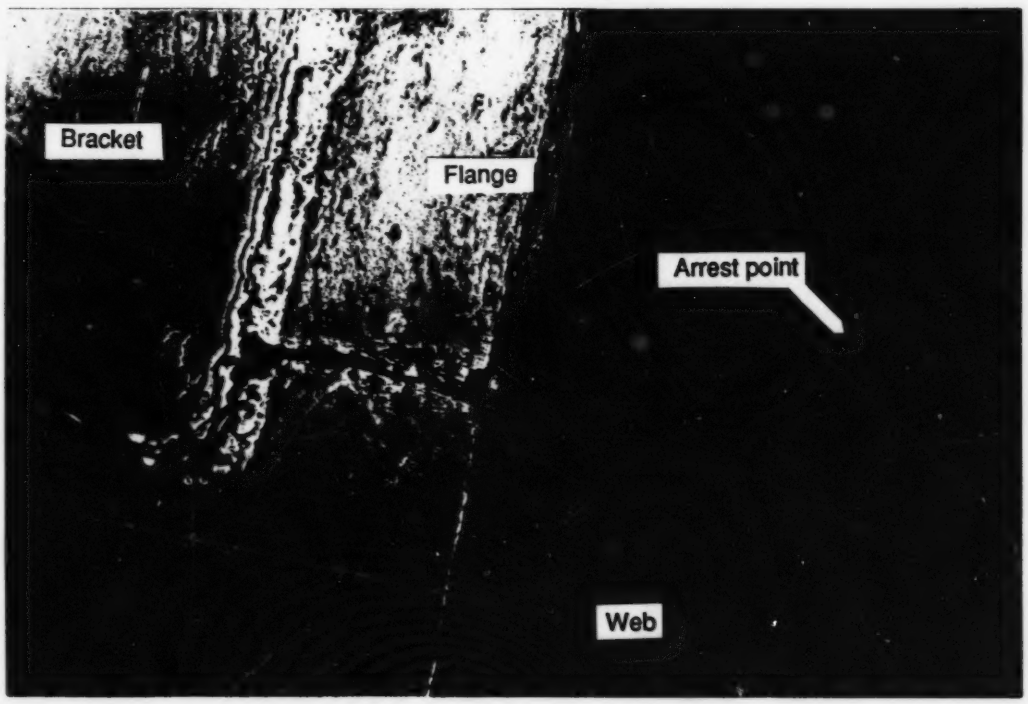

Figure 23. Appearance of fracture in the frame of the Louis St. Laurent due to local damage.

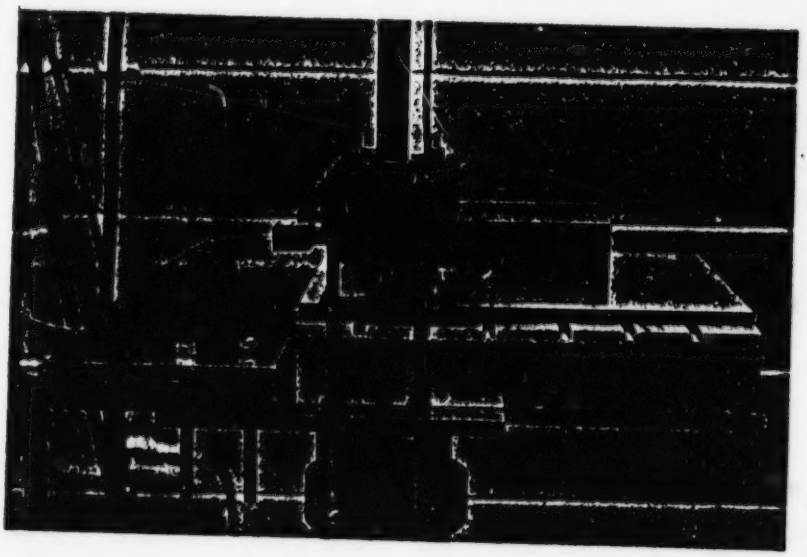

Figure 24. Set-up used by Ontario Hydro Research for conducting compact crack arrest tests.

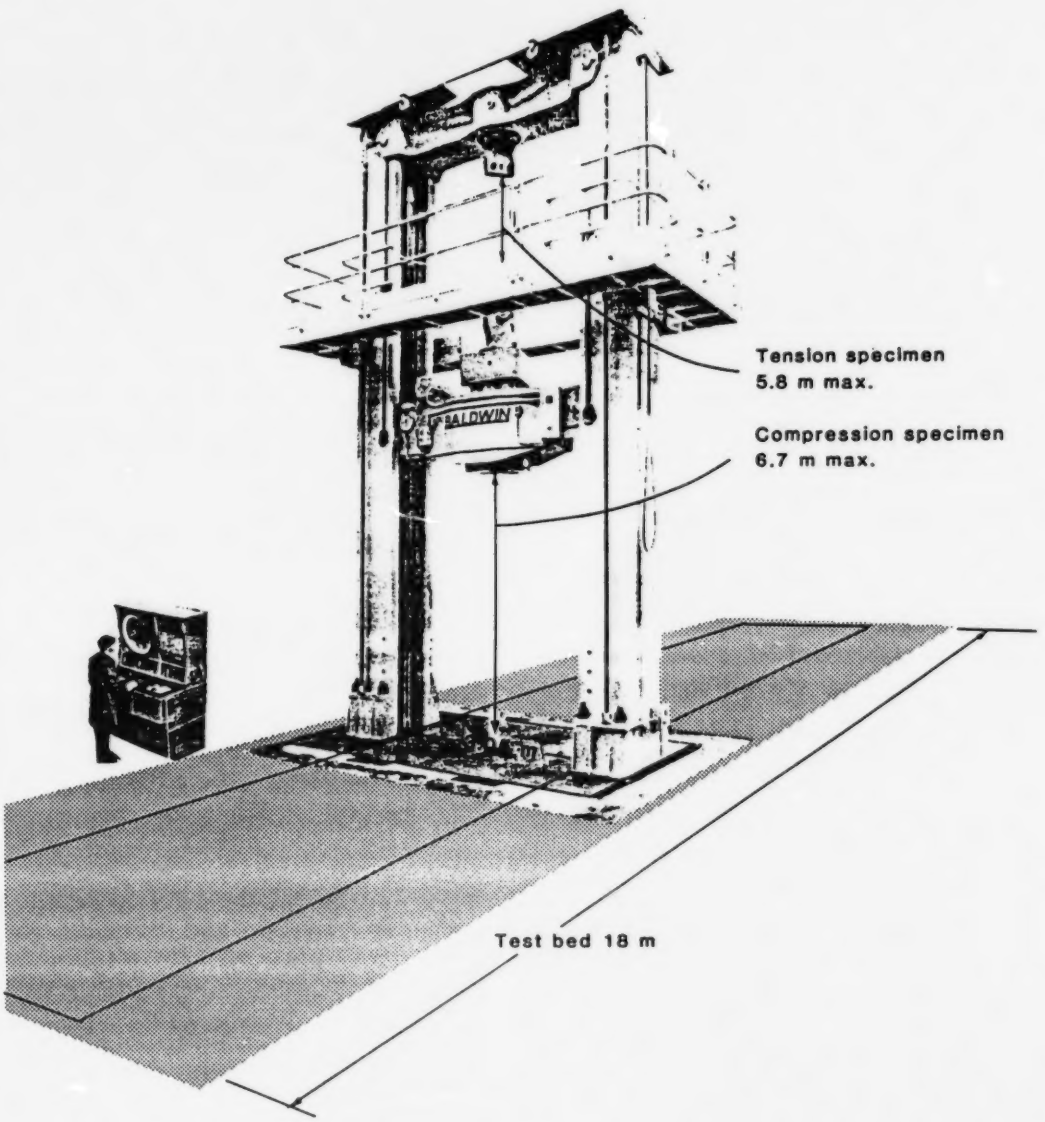

Figure 25. Baldwin universal testing machine at the University of Toronto.

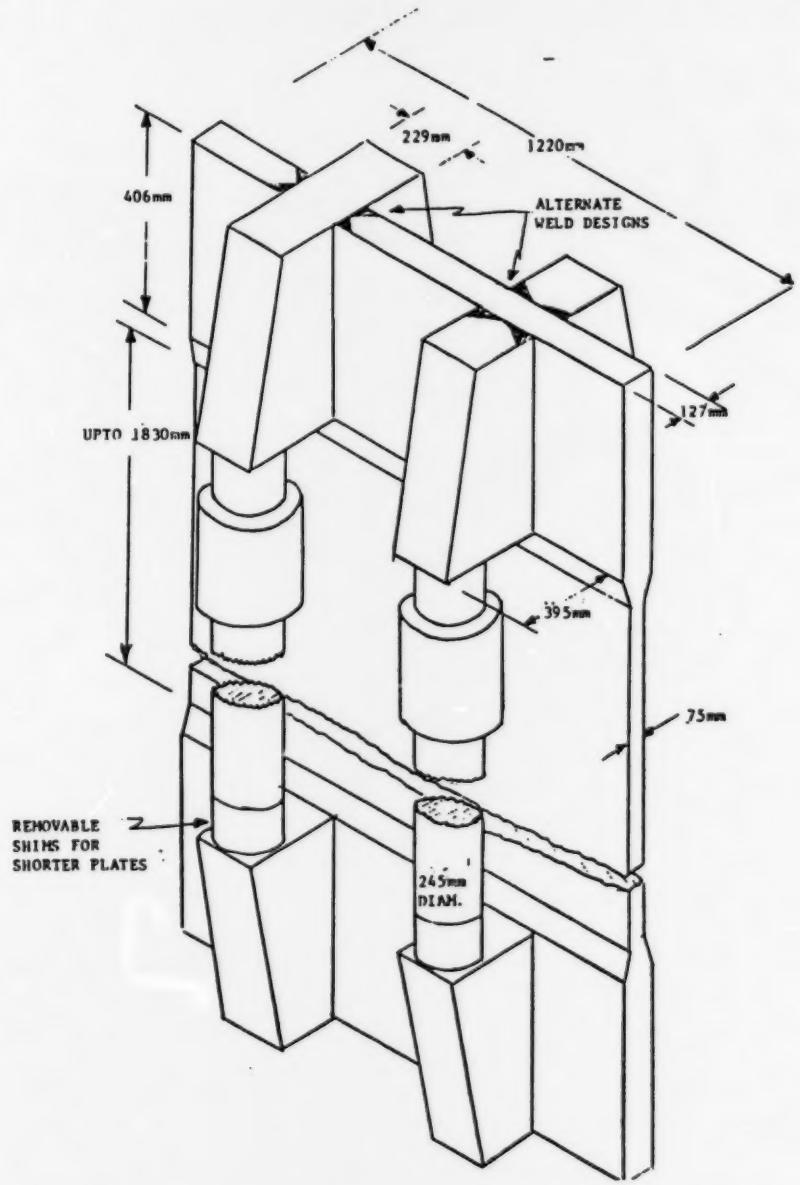

Figure 26. Dimensions of the wide plate test facility at WIC.

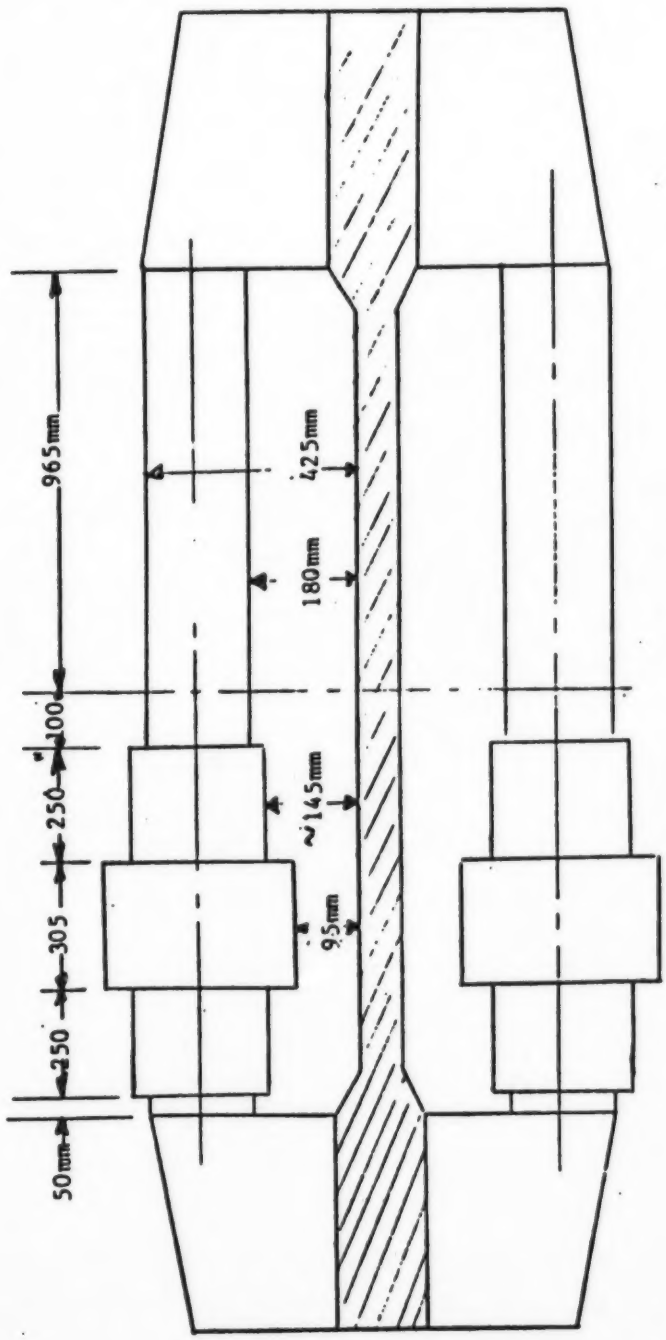

Figure 27. Clearance either side of the test plate in the wide plate rig at WIC.

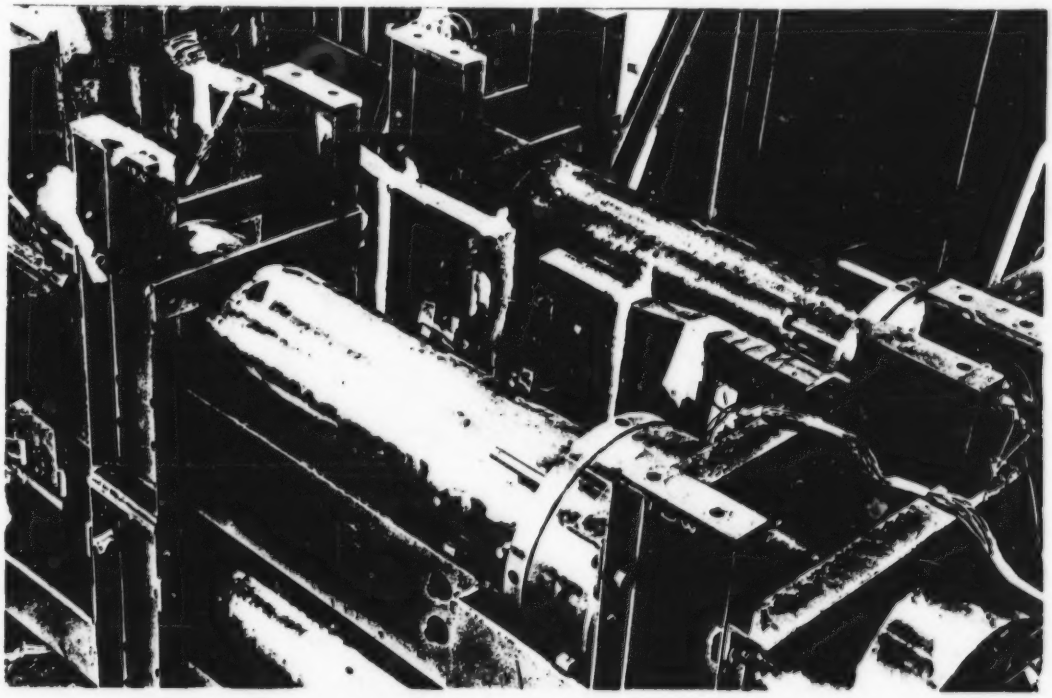

Figure 28. Photograph of the wide plate rig at WIC showing a fractured specimen.

Appendix—Crack Arrest Tests

Robertson Test

The Robertson test was an early test developed at the Naval Construction Research Establishment (U.K.) to evaluate ship plates. Full thickness plates are loaded to a constant stress and a crack initiated from an artificial source by impact. The test has been used with a continuous temperature gradient across the specimen by cooling the initiation side with liquid nitrogen or under isothermal conditions. The objective of the test is to determine the crack arrest temperature for the applied stress, and although an estimate is obtained from a single temperature gradient test, testing of several isothermal specimens is considered to provide a more reliable result.

In temperature gradient tests the position of arrest is usually identified with the visible broadening of the shear lip on the specimen surface. Results are presented as stress versus crack arrest temperature. The design of the test does not consider the effect of reflected stress waves and stored energy during crack arrest.

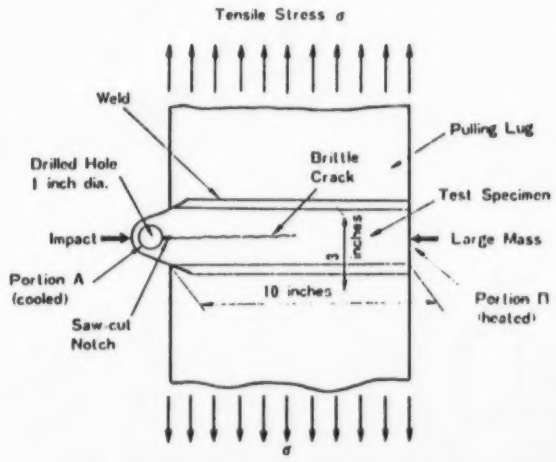

Figure A-1. The Robertson crack arrest test.

Esso Test

The Esso test is similar to the Robertson test but comprises two plates: one is the crack starter section and the other the test plate of interest. Test are loaded to a constant stress and conducted with a uniform temperature. A crack is initiated by driving a wedge into a sawed notch in the brittle starter section. The test is a 'go/no go' type with the crack either running completely across the specimen or arresting shortly after entering the test plate. It is common practice to conduct the test at the design stress and define the Esso brittle transition temperature as the lowest temperature at which the crack fails to propagate completely across the specimen.

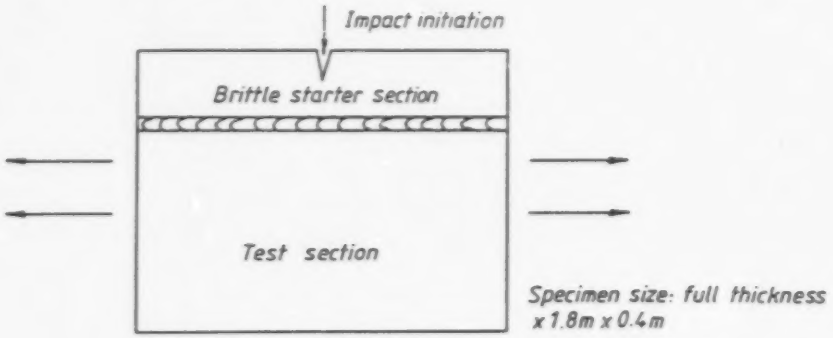

Figure A-2. The isothermal Esso test using two plates.

The Double Tension Test

The double tension test developed by Yoshiki and Kanazawa is similar to the Robertson test but overcomes some of the objections through careful design. Initiation of the crack is achieved by a separate load on a starter section. This load does not materially affect the main load on the test section. The starter section is held at a low temperature.

Tests may be conducted with a temperature gradient or under isothermal conditions. When gradient tests are used the crack arrest temperature is determined by the position of the tip of the arrested crack at the centre of the plate thickness. This temperature is substantially higher (~ 30°C) than the position used in the Robertson test.

Double tension test data is usually expressed as K_{ca} where K_{ca} is determined from the crack length and stress at fracture:

$$K_{ca} = \sigma (\pi a)^{1/2} \left(\frac{2W}{\pi a} \tan \frac{\pi a}{2W} \right)^{1/2}$$

Values of K_{ca} determined at various temperatures are normally plotted as log K_{ca} against $1/T$ (°K)

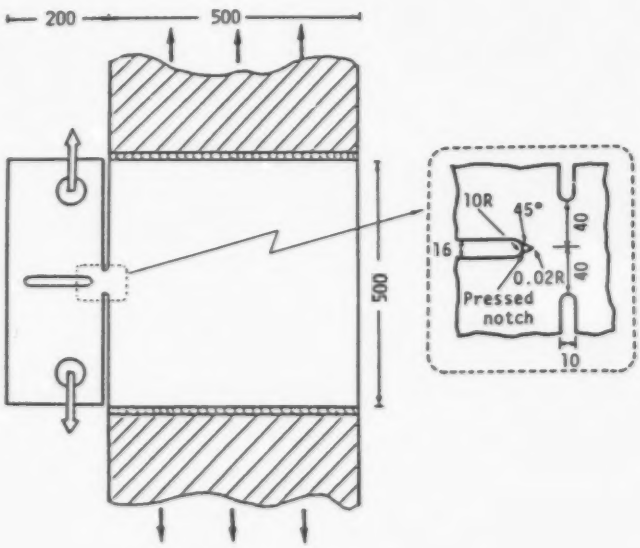

Figure A-3. The double tension test with standard dimensions.

Dual Plate Double Tension Tests

These have been used to evaluate arrester plates and provide for a larger propagating crack size than standard double tension tests when isothermal conditions are used. The test comprises three parts: a starter section (sub-tension) as in a standard double tension test; a propagation section in which the crack runs at high velocity; and the test plate. The propagation section may use a brittle weld or side grooves to guide the crack. It is welded to the test plate with a complete joint penetration groove weld.

The test is conducted as a 'go/no go' test, and results may be used directly to provide the stress/temperature crack arrest transition curve or to produce a value for K_{ca}. In the latter case the calculation of K_{ca} normally requires correction for load drop after arrest. Further correction is necessary if results are to compare with those of the standard double tension test and the empirical K_{eff}/K_{norm} curve may be applied. These tests have been particularly useful for evaluating steels for low temperature storage tanks where they closely simulate conditions in practice.

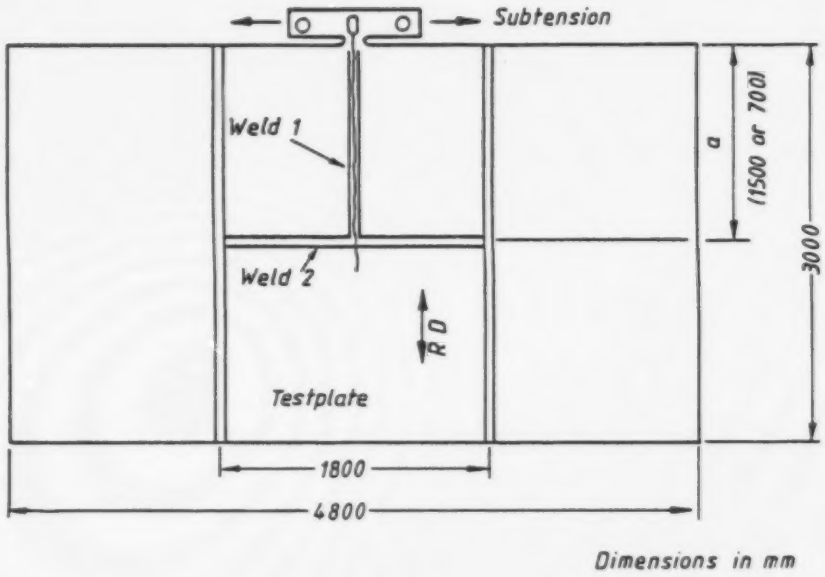

Figure A-4. The isothermal dual-plate double tension test.

Double Cantilever Beam (DCB) Test

Several geometries have been used for this test including rectangular, contoured and tapered specimens. A key feature of the test is the use of a blunt notch. This permits the specimen to be loaded to a value of stress intensity factor K much greater than K_{Ic}, the (initiation) plane strain toughness. Thus, as soon as a crack emerges from the blunt notch, it immediately becomes unstable and propagates rapidly until arrested.

A further feature is that wedge loading is inherently stiff with the crack propagating under conditions of constant load point displacement. As the crack progresses, the strain energy release rate decreases and the crack arrests. The test is also insensitive to the type of testing machine since little energy is exchanged between it and the specimen.

A dynamical analysis has been performed for the DCB test enabling a value for the (dynamic) arrest toughness to be determined.

The tapered version of the test has been widely used to determine K_{ca} by static analysis. For the geometry illustrated

$$K_{ca} = 0.0316\, y \left\{ \frac{E}{8}\, 0.0409\, exp\,(12.23 - 0.0409a) \right\}^{1/2} \text{ MPa}\sqrt{\text{m}}$$

where y = load point displacement at initiation (mm)
E = Young'a modulus (MPa)
a = Arrested crack length (mm)

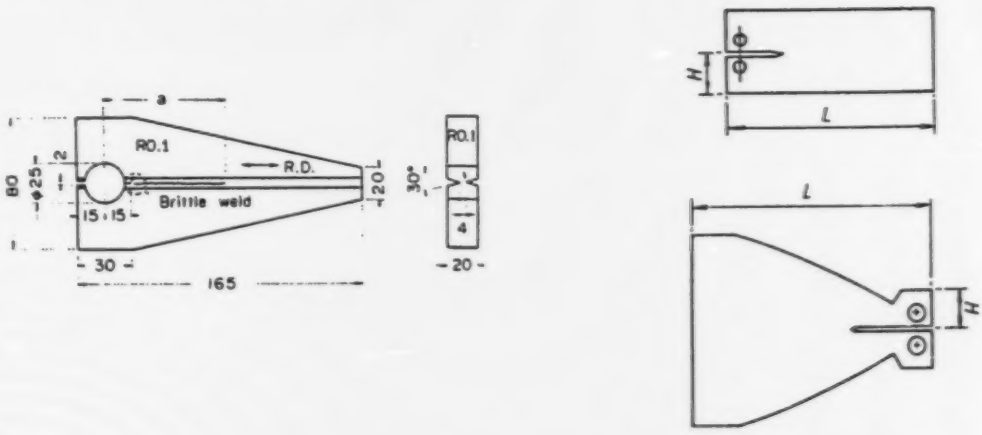

Figure A-5. The double cantilever beam specimen showing typical shapes.

Compact Crack Arrest Test

The compact crack arrest (CCA) test is designed to provide an estimate of K_{Ia}, the plane strain crack arrest toughness of ferritic steels using a static analysis. It is fully described in ASTM E1221-88. The test is conducted by forcing a wedge into a split-pin which applies an opening force across the crack starter notch. This causes a rapid run-arrest segment of crack extension. As in the double cantilever beam test from which this is derived, the strain energy release rate decreases as the crack extends thus providing for an arrest.

The nominal stress intensity factor at initiation, K_0, and the crack arrest toughness K_a are calculated from the original notch length and arrest crack length respectively, together with the crack mouth opening displacement. The crack opening loads are not measured directly because of the wedge loading method used but are derived from the displacements using a prior compliance calibration. A detailed cyclic loading procedure is specified in order to isolate any components of the displacement that do not contribute to opening loads.

The general arrangement for the CCA test is shown in Fig. A-6. The surfaces of the wedge, split pin, support block, and specimen hole are lubricated. The plate tested should be full thickness or adequate to achieve plane strain conditions. Side grooves across the specimen are used.

The starter notch is selected so that an adequate displacement is reached before crack initiation to ensure an appropriate crack extension before arrest. Different materials require different starter notch preparation procedures to produce an acceptable value of K_0. For low and medium strength steels (yield strength less that 700 MPa) a notched brittle weld is used.

The position of the arrested crack can be marked by heat tinting in the range 260 - 370°C for 10 to 90 minutes. The specimen is then broken open to measure the arrested crack length. The ideal fracture surface of a crack arrest specimen is flat, continuous, and with a straight front normal to the specimen surface. ASTM E1221-88 provides detailed guidance on the acceptability of fracture surfaces and arrest fronts obtained in practice.

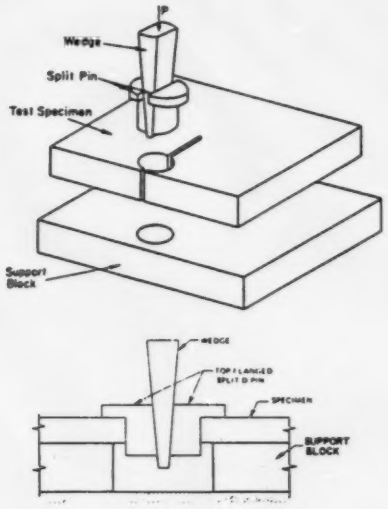

Figure A-6. Loading arrangement for the compact crack arrest test.

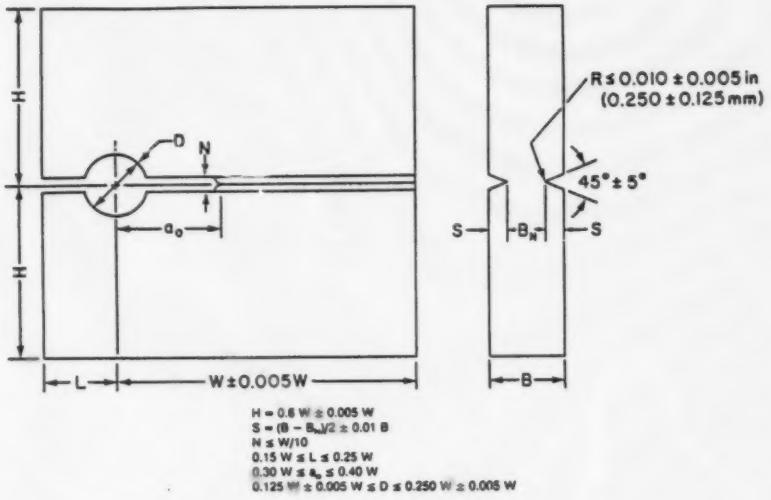

Figure A-7. Dimensions of compact crack arrest test specimen for low and medium strength steels.

The values of K_0 and K_a are calculated from

$$K = E\,\delta f(x)\frac{\sqrt{B/B_N}}{\sqrt{W}}$$

where

$$f(x) = \frac{2.24\,(1.72 - 0.9\,x + x^2)\sqrt{1 - x}}{(9.85 - 0.17\,x + 11x^2)}$$

and x = a/W
B = specimen thickness
B_N = net specimen thickness in crack plane
δ = crack mouth opening displacement

To ensure a consistent set-up of units, distance must be in metres and E in MPa to give K in MPa$\sqrt{m}$.

If a number of validity criteria are met to satisfy plane strain conditions the value of K_a is considered the plane strain value K_{Ia}. Because a fast running crack involves very high strain rates with an accompanying elevation of yield stress, plane strain conditions can be satisfied in low and medium strength steels at lower thicknesses than for static (initiation) measurements of K_{Ic}.

Drop Weight Test

The original drop weight test developed by Pellini can be considered a type of crack arrest test in that it determines the temperature at which a small pop-in from a brittle crack starter arrests in the steel. Small specimens are loaded in bending by an impact from a falling weight. Deflection of the specimen is limited to an amount corresponding to a tension stress across the face about equal to the dynamic yield stress of the material. The test is used as a 'go/no go' test to isolate the highest temperature at which the pop-in propagates across the specimen and fractures it. This temperature is known as the nil-ductility transition temperature (NDTT) and is a useful index of a steel's crack arrest properties. Full details of the drop weight test are in ASTM E208.

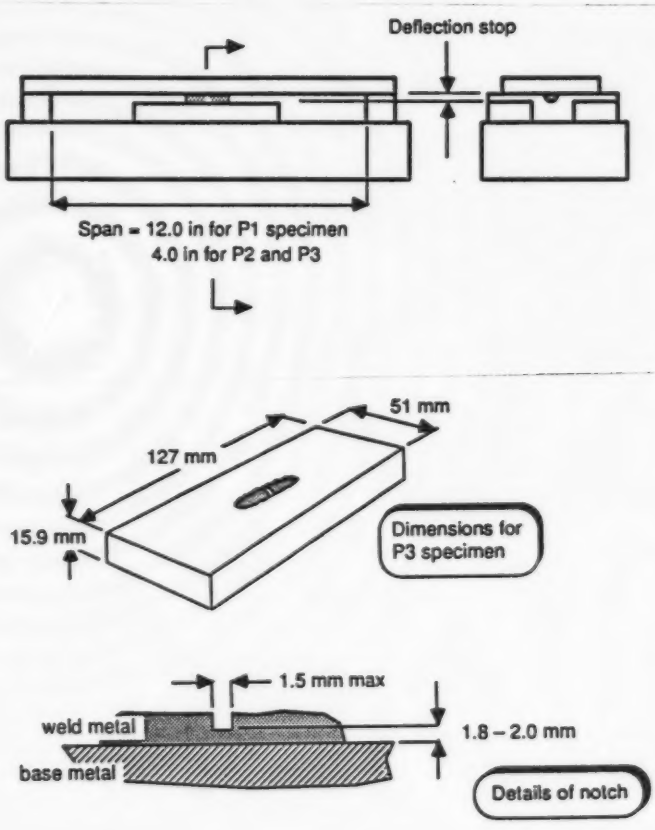

Figure A-8. The drop weight test for determining the nil ductility transition temperature (NDTT).

Short Crack Arrest Test

This test involves injecting a running crack into a loaded test plate held at a constant temperature and observing whether the crack arrests soon after entering the plate or not. It is a 'go/no go' type of test although there may be some potential for quantitative measurements from the length of the arrested crack. Since arrested cracks are short compared with the overall plate dimensions, the test is not influenced by reflected stress waves or stored energy of the system.

Tests can be conducted on parent material with the crack injected at a weld. In this configuration the test is similar to the Wells wide plate test. Alternatively, the crack can be injected into various parts of a weld. The starter plate is typically a 0.45% C steel which is loaded by a separate tension system as in the double tension test. To ensure the crack gets into the main test plate, brittle weld beads can be deposited beneath the starter plate. With this configuration the test simulates initiation from a brittle surface region.

Notches or grooves may be added to the plate on the side opposite to the starter section which have the effect of guiding the brittle fracture along the test plate for a short distance. Crack arrest may then occur when the crack leaves the notched region and the constraint relaxes. This provides a means for controlling the initial sizes of cracks running in the test plate.

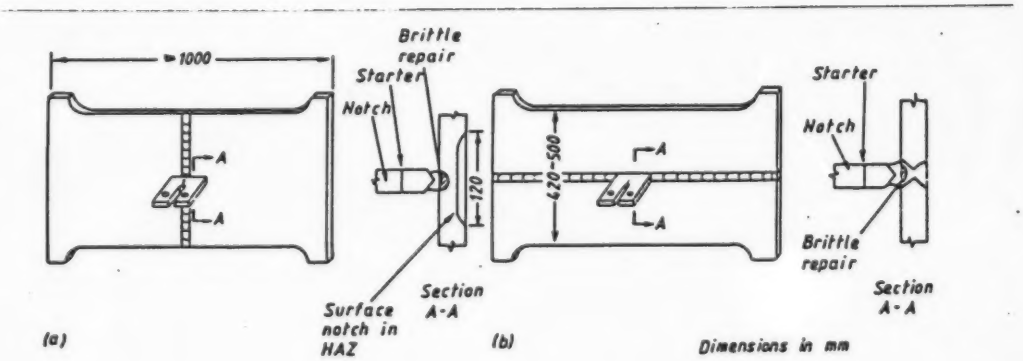

Figure A-9. The short crack arrest test showing configuration for testing (a) HAZ and weld metal and (b) base metal.